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IRON DEPOSITS OF THE CONGONHAS DISTRICT, MINAS GERAIS, BRAZIL.[1]

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CONTENTS.

	PAGE
Abstract	639
Introduction	640
Acknowledgments	641
Geography and mining	642
Geologic setting	643
Basement complex	643
Metamorphosed sedimentary and volcanic rocks	644
Minas series	645
Itacolumi series	647
Structure	648
Green schists and associated intrusive rocks	650
Origin of itabirite	651
The hematite deposits	657
Description	657
Origin	665
Source of the ore-forming solutions	667
Distribution and localization of the deposits	669
Comparisons with hematite ores of other areas	670
Weathering	671
Weathering of itabirite	671
Weathering of hematite ores	674
Summary	675
Bibliography	675

ABSTRACT.

Various origins have been proposed for the itabirite and associated hematite ores of Minas Gerais, Brazil. The U. S. Geological Survey, in coöperation with the Brazilian Departamento Nacional da Produção Mineral, has undertaken a comprehensive program of mapping of these

[1] Publication authorized by the Director, U. S. Geological Survey. Presented at the Boston meeting of the Geological Society of America and Society of Economic Geologists, November 13–15, 1952.

Precambrian deposits, which bear many similarities to other Precambrian iron formations.

Itabirite is a finely laminated quartz-iron oxide rock with more or less dolomite, corresponding to James's oxide facies. It occurs principally in the middle group of the Minas series—a eugeosynclinal assemblage of quartzite, schist, chemical precipitates, graywacke, and volcanic rocks. Iron and silica were precipitated rhythmically in a shallow restricted basin under somewhat acid conditions that inhibited the precipitation of carbonates. Erosion of moderately deformed rocks of the Minas series furnished sediments for the overlying conglomeratic Itacolumí series. Severe post-Itacolumí deformation folded and thrust-faulted rocks of both series; the accompanying regional metamorphism recrystallized the chert and iron oxide to quartz, specular hematite, and minor amounts of magnetite. Ultramafic intrusions antedate this diastrophism; granodiorites and various basic dike rocks are younger.

Hydrothermal replacement of breccia zones in itabirite and of dolomitic beds associated with the iron formation produced high-grade specular hematite ore nearly free of impurities. The areal distribution of the deposits indicates that the solutions followed fault zones. Heated meteoric water may have been responsible for the replacement, as minerals of obvious magmatic origin are absent.

Since early Tertiary time the area has been uplifted several thousand feet. Leaching and cementation related to the present surface have modified both the iron formation and the hematite deposits, giving rise to various types of commercial ore.

INTRODUCTION.

A NUMBER of theories have been advanced to explain the origin of the many Precambrian sedimentary iron formations and associated ore deposits throughout the world. Although specific features of mineralogy and geologic occurrence vary somewhat from place to place, and have perhaps been emphasized too much in the past, there is little doubt that the similarities between these formations far outweigh their dissimilarities; hence the results of studies in one region may aid in explaining perplexing features thousands of miles away. The present contribution to the already voluminous literature gives a few more details resulting from several years of field work on the Brazilian "itabirite" iron formation and the rich hematite deposits that occur within it.

These deposits, whose existence was vaguely known for centuries, were called to the attention of the geologic and mining professions in 1910 by Derby (6).[2] He estimated the reserves at not less than several billion tons but emphasized the lack of specific data on tonnage and grade. Since that time various studies have been made leading toward a better understanding of the geologic setting and origin of these ores, but much remains to be done. Harder and Chamberlin (22) attributed the iron formation to the precipitation of iron hydroxide by bacteria in a shallow sea where only minor amounts of clastic quartz grains were being deposited. The high-grade hematite ores were believed to be syngenetic, formed by the accumulation of nearly pure iron oxide in localized areas where quartz and other impurities were not being deposited. Leith and Harder (26) pointed out the supposed differences be-

[2] Numbers in parentheses refer to Bibliography at end of paper.

tween these ores and the Lake Superior type, and Harder (21) refuted the theory advanced by Gathmann (10) that the high-grade ores resulted from the surface leaching of silica from the iron formation. Freyberg (8, 9) rejected the role of bacteria and advocated chemical precipitation of the iron as oxide or hydroxide, recalling Vogt's explanation (34) for the precipitation of the Norwegian itabirites that are closely associated with dolomitic marbles. He agreed with Harder and Chamberlin on the clastic nature of the quartz, and on the origin of the pure hematite ores. Sanders (31) appears to have been the first to attribute the hematite ores to later enrichment of the iron formation. He was greatly impressed by the number of basic dikes that cut the itabirite and hematite bodies at Itabira and advocated a close genetic relationship between them and the ore-forming solutions. Grosse (12), in his study of the Fábrica area near Congonhas, described the pure ores as epigenetic stocks, inferring their origin to be through enrichment of the iron formation, but he did not go into the detailed evidence or a detailed explanation of the process. Guimarães (18, 19, 20), in various publications from 1931 to 1951, has discussed the origin of the itabirite, presenting various hypotheses. In his most recent paper on the subject (1951) he emphasizes the volcanic materials, both tuffs and flows, that are associated with the iron-rich sediments. He believes that the original source of the iron was in large part, at least, volcanic and that the iron may have been partly precipitated directly as hydroxide, or possibly as carbonates and hydrous silicates, and partly concentrated during regional metamorphism by the selective removal of other constituents, accompanied by minor transportation and redeposition of the iron. Barbosa (1) pointed out the similarities between the itabirite and the only moderately deformed, unmetamorphosed iron formation at Urucum in western Mato Grosso, Brazil, and suggested that the itabirite was deposited as chemical precipitates of iron oxide and colloidal silica that were recrystallized to the present hematite-quartz rock by regional metamorphism. He called attention to nodular structures in some of the itabirite very reminiscent of cherty nodules in the Urucum iron formation. Tyler (32), in a laboratory study of itabirite samples collected by Harder, found no evidence of the heavy accessory minerals always present in quartzitic rocks of clastic origin, and pointed out the similarity of the mosaic texture of the quartz to that of recrystallized cherts of the Lake Superior iron formations. Barbosa and Tyler thus effectively put an end to the long-held misconception that the itabirite is fundamentally different from the cherty iron formations of other regions.

ACKNOWLEDGMENTS.

In spite of the extensive literature on the region (and the papers cited are only a few of the more important ones), no detailed areal mapping on an adequate scale had been carried out, except for a few isolated deposits, until the U. S. Geological Survey, in coöperation with the Brazilian Departamento Nacional da Produção Mineral, undertook a long-range program in 1947. The author developed the ideas presented here while a member of the mapping party; he owes much to discussion of the problems with his colleagues,

particularly J. V. N. Dorr, 2d and Joel B. Pomerene of the U. S. Geological Survey and Aristides Nogueira da Cunha of the D.N.P.M., but responsibility for the ideas must be his alone.[3] He is also indebted to W. D. Johnston, Jr. and R. M. Garrels of the Geological Survey, who reviewed this paper and made many valuable suggestions. It should be emphasized that this paper is in the nature of a progress report, based largely on the mapping of only a small part of the total ferriferous area, and it is natural to expect that conclusions reached here will be modified or even changed radically as the work progresses.

GEOGRAPHY AND MINING.

The deposits of the Congonhas district lie in central Minas Gerais, about 200 miles inland from the coast near the southern end of the Serra do Espinhaço, the "Backbone Range" of eastern Brazil (Fig. 1). The country

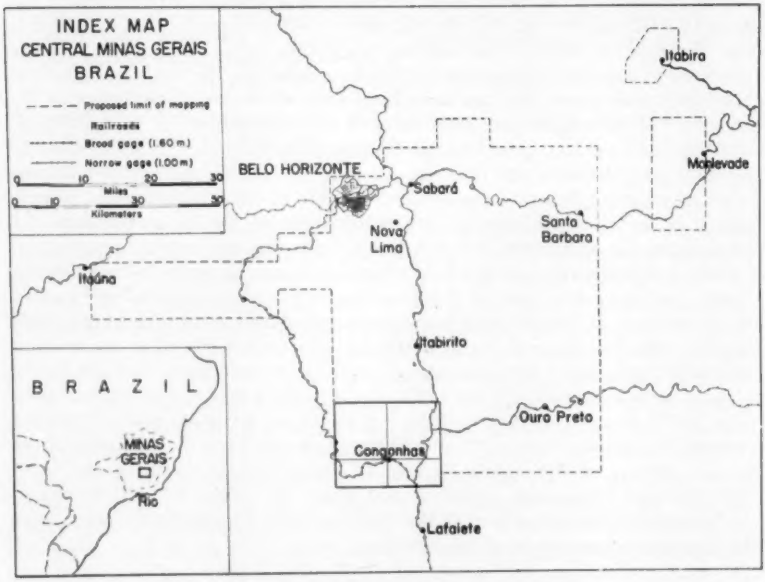


FIG. 1. Index map of central Minas Gerais, Brazil.

is rugged, with altitudes ranging from about 2,000 to 6,000 feet. Although the region lies within the tropics at about 20° S. latitude, the climate is temperate and healthful. Most of the rain, which averages about 55 inches

[3] Since the present paper was completed an earlier one has appeared, which anticipates certain of the concepts presented here. It is "Origin of the Brazilian Iron Ores" by John Van N. Dorr, II, Philip W. Guild, and A. L. M. Barbosa: Symposium sur le Fer, vol. I, p. 286–298, XIXth Internat. Geol. Congress, Algiers, 1952.

per year, falls during the summer—November to February; the winters are cool and dry.

Two railroads reach into the area, one from Rio de Janeiro and another from Victoria on the coast due east. The Victoria-Minas is a meter-gage road, designed primarily for ore transport, that descends the valley of the Rio Doce on a steady grade. The other railroad is broad-gage (1.60 m), but as it has to carry all sorts of cargo and crosses two divides to reach Rio de Janeiro, its ore capacity is not great. Poor to fair highways link the district with Rio and other cities, and connect the various towns within it. Belo Horizonte, a modern city of some 350,000 that is the capital of the state, has good plane service to all parts of Brazil.

Although iron was first smelted from local ores in primitive forges during the 18th century and at least two small blast furnaces were erected early in the 19th century, it was not until about 1890 that any sustained production of pig iron was attained. Since that time some 5,000,000 tons of iron and steel have been made with charcoal. The local capacity has risen steadily to its present one of about 400,000 tons per year from a number of small furnaces. In 1946 the Volta Redonda steel mill near Rio de Janeiro began operation of a 1,000-ton blast furnace that uses coke made from Brazilian and imported coal. A second blast furnace is under construction. This mill, the largest in South America, gets all its ore from Minas Gerais.

Exports at present are only a small fraction of the potential production, and are limited entirely to the highest grade lump ores containing 68 to 70 percent iron. The greater part comes from the Itabira district (35) on the Victoria-Minas railroad. Most of the transport capacity of the western part of the district is used for manganese ores and to supply the steel mill at Volta Redonda.

The high-grade hematite deposits occur as isolated masses in the iron formation, which crops out either on the crests or along the flanks of prominent ridges within the areas shown by the dashed lines in Figure 1. The total length of outcrop is not less than 200 miles; the thickness varies greatly, attaining more than 3,000 feet in some places. As the average grade of the formation is perhaps 40 percent, the quantity of iron involved is enormous. The Congonhas district mapped by the author, on which this paper is chiefly based, lies in the southwest corner of the ferriferous area.

GEOLOGIC SETTING.

Basement Complex.

The oldest rocks of the Congonhas district are foliated, medium-grained gneisses composed chiefly of microcline, quartz, plagioclase, biotite, and muscovite, intruded by nonfoliated acid igneous rocks of granitic to quartz monzonitic composition. The nature of the contact between these crystalline rocks and the overlying sedimentary rocks is not clear. The gneisses appear to be migmatized sedimentary rocks that have undergone at least one more period of metamorphism and intrusion than the rocks of the overlying series, which lie unconformably on the nonfoliated granite in places. On the other

hand the bedding of the younger rocks is parallel to the foliation of the gneiss for many miles along the contact, and there are narrow pegmatites, tourmalinized zones, and coarse kyanite veins in the lower beds of the younger sequence. It seems probable that the intrusive bodies in the gneiss are of at least two ages, one older and the other younger than the sedimentary rocks.

Metamorphosed Sedimentary And Volcanic Rocks.

Two series of metamorphosed sedimentary rocks containing varying amounts of volcanic material have been recognized in the southern part of the

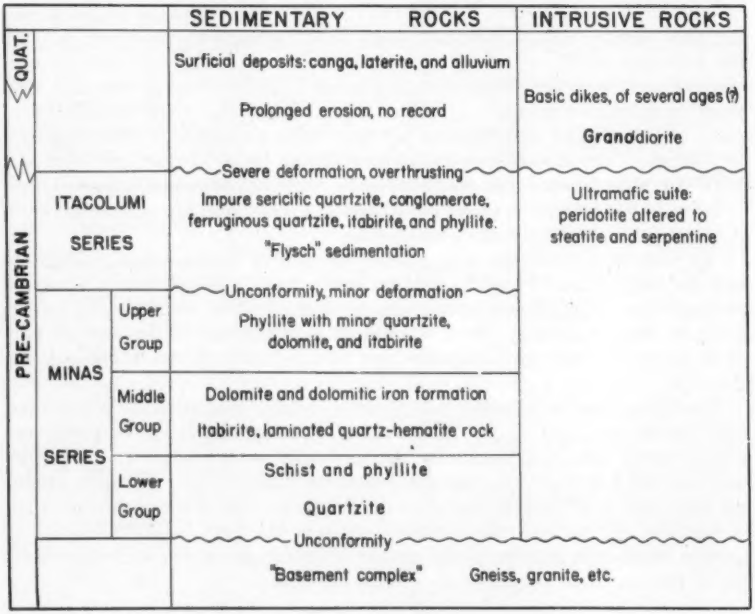


FIG. 2. Geologic column of the Congonhas district.

Serra do Espinhaço (Fig. 2). The lower one, which contains most of the iron, is the Minas series; the upper one is the Itacolumi series. They are considered to be Precambrian because 1) they are more metamorphosed and more complexly deformed than a sparsely fossiliferous Silurian (?) series that unconformably overlies them to the north; and 2) they resemble Precambrian rocks from other parts of the world that have comparable lithologies, particularly the peculiar cherty iron formations, and comparable grades of metamorphism.

Minas series.—The Minas series may be divided into three groups that are generally recognizable within the Congonhas district and elsewhere in the ferriferous area. The lower group consists of medium- to coarse-grained, well-bedded white quartzite with minor sericite. In places, both along the strike and vertically in the section, the mica increases in amount and coarseness to form a quartz-muscovite schist. In general the lowest beds are clean quartzite and the proportion of mica increases upward, but with one or more alternations. The upper beds of the group are highly micaceous wherever they are exposed within the district, so that the overlying itabirite rests on schist. The lower group is notable for being the only one in the series that is almost completely free of iron. It ranges in thickness from 100 m or less in the southwest corner of the district to about 650 m at the northern edge; elsewhere the lower group reaches a thickness of at least 900 m. It must be emphasized that the stratigraphic thicknesses of all the sedimentary rocks have been obscured by isoclinal folding, plastic flow, and repetition of beds by faulting.

The middle group is composed of itabirite and dolomite. To it belong most of the commercial deposits of iron and many of the manganese deposits (27) of central Minas Gerais. Deposition of the iron began rather abruptly, with only a thin transition zone separating the ferruginous rocks from the underlying micaceous schist. Itabirite is a laminated rock composed principally of granular quartz and specular hematite, although dolomite and in places amphibole (tremolite and anthophyllite) are essential constituents of some beds. In the dolomitic beds, whether amphibole is present or not, the iron oxide is magnetite. Siderite and pyrite have not been observed. The itabirite is uniformly fine-grained, with interlocking mosaic-textured quartz grains averaging 0.1 mm in diameter and specular hematite crystals, usually irregular but in places with well-developed basal faces (0001), that range from 0.001 mm or less to about 0.1 mm across. Where dolomite is present it tends to a somewhat coarser texture, with a grain size of a few tenths of a millimeter. Amphibole needles may reach a length of several millimeters. The individual laminae, which range in thickness from 1 mm or less to a few centimeters, vary in their proportions of iron oxides to other minerals (Figs. 3, 4).

The term "itabirite" has been variously defined, and has meant different things to different authors, but the most widely accepted usage, and the one that seems to have the most logical genetic basis, restricts it to the laminated rocks containing iron oxide and visible quartz or other light-colored constituents. This excludes the ferruginous quartzites and conglomerates, which are not laminated; the high-grade ores, which do not contain visible quartz in layers; and the somewhat ferruginous dolomites with scattered magnetite octahedra.

All gradations seem to exist from siliceous itabirite through quartz-dolomite-magnetite itabirite to almost pure dolomite that is being quarried for metallurgical stone. Some dolomite beds contain angular fragments of two types, one of very pure carbonate and the other of finely granular quartz, in a matrix of siliceous, often magnetite-bearing dolomite (Fig. 5). These

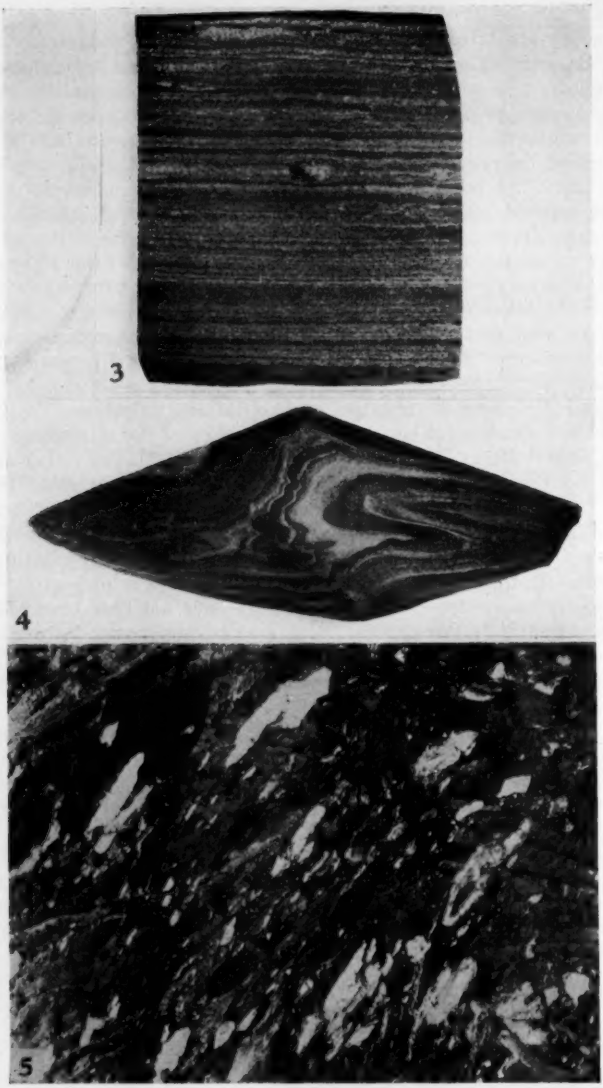


FIG. 3. Siliceous itabirite; light-colored layers are quartz-rich, dark layers hematite-rich. Polished face. × 1.

beds are almost certainly intraformational breccia conglomerates; the quartz is interpreted as recrystallized chert. Talc is a common mineral in the ferruginous dolomite, and especially in the somewhat dolomitic itabirite, where it is concentrated along certain laminae, much like mica in a schist. Chlorite is also common in the dolomite, both along bedding planes and in joints and carbonate veinlets. Pyrite cubes occur sparingly in some dolomite zones, but they have not been seen in association with iron oxides.

The proportion of dolomite to itabirite varies greatly from place to place. Throughout much of the district dolomite is rarely seen, perhaps because it has weathered, but on the eastern side it makes up probably one-half of the section. Dolomitic itabirite may occur at any horizon, but the purer dolomite is more common in the upper part of the group. Some dolomitic lenses that are overlain by itabirite are separated from it by thin beds of rutile-bearing chlorite schist; exposures are too poor, however, to confirm that this sequence holds everywhere.

Like the lower group, the middle group thickens from about 100 m at the southwest corner of the district to some 700 m in a few places, but it is not known how much of this thickening is due to deformation rather than to original differences in sedimentation.

The upper group is composed chiefly of sericite phyllite containing fine-grained quartz and in places notable amounts of graphite that grades into sericitic quartzite lenses. Thin lenses of itabirite, perhaps only a meter or two thick, yet hundreds of meters long, are relatively common. Their presence seems to be the best criterion for distinguishing the upper group from the quartzite and schist of the lower group, for no sure lithologic characteristics applicable in outcrop or in thin section have been found for identifying the various quartzitic and argillaceous members of the series. Impure dolomitic lenses and thin, nonlaminated ferruginous quartzites also occur. Various rocks of volcanic affinities have been recognized, and it should be mentioned that Guimarães and Barbosa (19) noted the abundance of albite, rutile and titanite, and apatite in thin sections of cores from several deep holes drilled at various spots to the north of the Congonhas district. They attributed these minerals to tuffaceous components intimately mixed with terrigenous sediments. The thickness of the upper group is not known, but it appears to be several times that of the lower group and probably reaches several thousand meters.

Itacolumí series.—A thick sequence of quartzite with intercalated conglomerate and minor quantities of phyllite unconformably overlies the Minas series. At the type section in Pico Itacolumí, 18 miles east of the Congonhas district, these rocks are fairly "clean" and well-sorted, but near Congonhas they consist

FIG. 4. Tightly folded siliceous itabirite; the light-colored layers are hematite-rich. Fold axes parallel the regional lineation. Polished face, reflected light. × 1.

FIG. 5. Weathered dolomite breccia conglomerate. White areas are fine-grained quartz (recrystallized chert ?); the dark matrix is limonite, quartz, etc., produced by weathering of impure ferruginous dolomite. Largest fragment is 9 cm long.

of "dirty," very sericitic quartzite, ferruginous quartzite, phyllite, and conglomerate containing pebbles or boulders derived from the underlying rocks. Many of the conglomerate fragments, which range in size from coarse sand to boulders about 50 cm across, are well rounded (Fig. 6). They are chiefly of vein quartz; but quartzite, schist, and itabirite fragments are abundant. Very fine-grained hematite is a prominent constituent of the matrix of some beds. It fills the interstices between rounded quartz grains that frequently have overgrowths of secondary quartz. A few thin beds are virtually pure hematite. In addition to the ferruginous quartzites and conglomerates of clastic origin there are lenses of true itabirite with the characteristic fine lamination. The principal lens reaches an apparent thickness of several hundred meters and is in itself indistinguishable from parts of the itabirite member of the lower series, except for the presence of angular breccia conglomerates zones (Fig. 7) and several quartzite members. It is all very siliceous, and no trace of dolomite either as lenses or as a minor constituent of the itabirite itself has been found.

These rocks were originally described by Barbosa (1) as a formation of the Minas series, which he called Santo Antonio from the peak of this name a few miles north of Congonhas. The writer and others, including Barbosa himself, now correlate these rocks with the Itacolumí series, as what may be termed the "Santo Antonio facies."

The thickness of the series must vary rapidly from place to place, as it seems from the character of the sediments that they are a Flysch type, laid down in local basins as the surrounding lands began to rise and be eroded. Isolated patches are known in various places in the ferriferous area, and it seems likely that additional ones will be found as mapping progresses.

Structure.

Moderately deformed itabirite pebbles in the conglomerates of the Itacolumí series are evidence of a weak post-Minas orogeny accompanied or followed by uplift. However, both the Minas and the Itacolumí rocks were severely folded and metamorphosed in post-Itacolumí time, with the development of pronounced cleavages and a prominent pencil structure that transects all the rocks. This lineation is not only the most prominent structural element of the rocks, with the possible exception of the generally well-preserved bedding, but it is also the most constant in attitude. Although bedding, and hence whole ranges, trends in all directions in the ferriferous area, the linear structures maintain a rather constant direction within some 20° to 30° of east and ordinarily plunge gently to moderately in that direction. This lineation is expressed by: 1) axes of major folds and innumerable drag folds, 2) intersections of cleavages with bedding, 3) intersections of two or more cleavages, 4) elongation of mica clusters in quartzite, 5) elongation of pebbles in conglomerates, 6) orientation of elongated fragments in the dolomite breccias, 7) the long axes of most, perhaps all, of the hematite deposits, 8) ore shoots within the bedding plane gold-quartz vein of the Passagem mine near Ouro Preto, and 9) the trend and pitch of the great Morro Velho gold deposit and

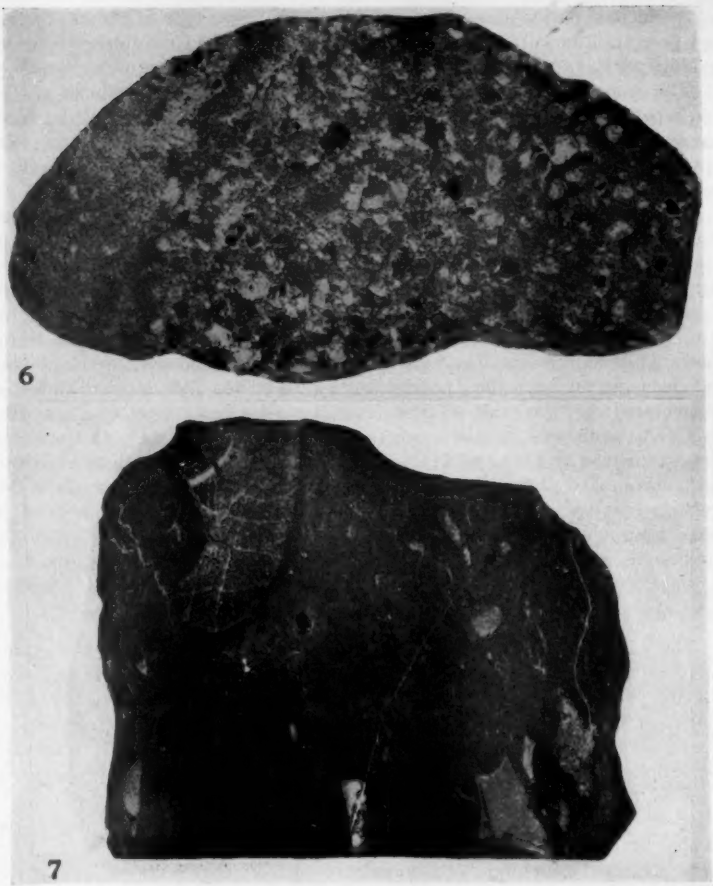


FIG. 6. Fine-grained conglomerate, Santo Antonio facies of the Itacolumí series. Quartz and itabirite pebbles in a matrix of fine quartz, hematite, and muscovite. Polished face, × 1.

FIG. 7. Angular breccia conglomerate of recrystallized chert (?) fragments in matrix of fine quartz and hematite. Polished face, × 1.

smaller ore bodies near Nova Lima. A prominent joint set is more or less normal to this lineation. The author has no ready explanation for this phenomenal uniformity of trend, which in many places is normal or oblique to the major structures, but he offers it as evidence of the profound deformation that these rocks underwent in post-Itacolumí time. The uniformity

argues for one major diastrophism that imposed some type of plastic(?) flow and elongation on all the rocks without destroying even the finely laminated bedding planes of the itabirite.

The orogeny culminated in extensive thrust faulting that produced a four-fold repetition of the itabirite in the Congonhas district. Traces of the faults are arcuate, concave to the east, and it seems probable that thrusting was from east to west, in the direction of the lineation, which would, therefore, lie in the *a* petrofabric direction.

Stresses of a different nature produced a great transcurrent fault that crosses the district from east to west and cuts off the southern ends of the quartzite and itabirite ridges. The fault plane dips about 45° south where it can be measured. Fracturing and drag of the quartzites indicate that the southern block moved upward and to the west. The evidence for dating of this movement is conflicting, for on the one hand the fault cuts the thrust planes while on the other hand quartzite beds are dragged parallel to the fault and cleavages maintain their normal northward trends and eastward dips. It is suggested that the fault resulted from the same general set of forces that produced the thrusts, and is hence roughly contemporaneous with them, but that it remained as a zone of weakness in the crust along which later readjustments have taken place. It is no doubt significant that the rocks south of this fault do not have the east-trending lineation universally found north of it. The author will discuss the structure in detail in a future paper when the quadrangle maps are published.

Green Schists And Associated Intrusive Rocks.

The east-west transcurrent fault marks the limit of typical Minas and Itacolumí rocks, for immediately south of it a thick sequence of rather nondescript, deeply weathered green schists crops out that is intruded by numerous igneous rocks of several types. The schists are composed of quartz, plagioclase feldspar, biotite, chlorite, muscovite, tremolite, actinolite, talc, calcite, spessartite, and other minerals in widely varying proportions. Some of the coarse-grained well-bedded rocks strongly resemble water-laid tuffs; others are more or less typical graywackes, with angular quartz and feldspar fragments in a matrix of fine biotite, chlorite, and sericite. Very finely dispersed graphite(?) is commonly seen in thin sections, and pyrite cubes are present in places. A number of siliceous itabirite lenses ranging from a few meters down to 10 cm or so in thickness crop out for several kilometers along a narrow zone; otherwise no marker beds are recognizable. As detailed structure cannot be worked out, the thickness of this section is unknown. It crops out continuously for more than 20 km within the Congonhas district, however, and continues an unknown distance to the east; it must therefore be very thick.

Extensive masses of steatite with schistose borders and numerous conformable lenses of talc schist represent ultramafic intrusives that antedate the orogeny. Massive or only slightly foliated granodiorite stocks and dikes cut the green schist complex and associated steatite, and are clearly post-orogeny.

Various dark dike rocks with the approximate composition of diabase cut all these rocks. Their textures range from fine-grained ophitic to rather coarse granitoid; most contain about 50 percent of hornblende or chlorite derived from it, with plagioclase and alteration products, and with minor amounts of biotite, epidote, ilmenite and titanite, and magnetite. They may well be of several ages and affinities, but little effort has been made to distinguish them.

The green schist sequence has been called Archean, pre-Minas Proterozoic, and Minas series equivalent. The writer is inclined to the last view, although recognizing that these rocks may be older. Reasons for considering these rocks pre-Minas are 1) their older "aspect" and extensive development in areas long considered as the "crystalline complex"; 2) the abrupt change in lithology and absence of the quartzites and thick itabirite-dolomite sequence; and 3) the abundant intrusive rocks that are apparently lacking in the typical Minas series north of the fault. However, careful mapping shows that at least part of this older "aspect" is due to thermal metamorphism by the granodiorite stocks, as typical Minas phyllites are altered to identical rocks in the aureole around a large granodiorite mass in the northeast corner of the district. At least part of the granodiorite is post-Minas therefore, and its relative scarcity in the phyllite areas north of the fault probably accounts for the "younger" appearance of these rocks, since the contact action tends to obscure bedding and produce rocks more susceptible to deep weathering. Serpentines have been described in the Minas series from a number of places within the ferriferous area, although they were not found in the northern part of the Congonhas district, so their presence or absence does not furnish a reliable criterion of age. The dark dike rocks cut both the green schist and the Minas series, as well as the granodiorite, and hence are useless for dating purposes.

The general sequence of clean quartzites and thin schists, chemical precipitates, and thick phyllites with minor tuffs and admixed tuffaceous material strongly indicates eugeosynclinal sedimentation. The green schist-graywacke-tuff sequence with its thin itabirites suggests deeper-water, offshore sediments that were deeply infolded, intruded, and later faulted into juxtaposition with the shallow-water facies. This view is substantiated by the fact that no sharp break can be found between the phyllites of the Minas series and the green schists along the southeast flank of the western range, where the transcurrent fault seems to die out.

ORIGIN OF ITABIRITE.

There can be little doubt that itabirite originated as chemical precipitates of iron compounds, silica, and in places carbonates of calcium and magnesium, with variable but generally minor quantities of alumina, phosphates, and other substances. Manganese compounds were also precipitated in relatively minor amount; they have not been discussed here because: 1) they are not believed to have affected the main course of iron precipitation appreciably and 2) the discussion of all the aspects of their precipitation and concentration would expand this paper enormously and unnecessarily. Regional metamorphism caused the recrystallization of the sediments, expelling any water combined with the original minerals and producing the assemblage hematite

(or magnetite), quartz, "dolomite" (equals calcium-magnesium carbonate of varying Ca-Mg ratio), and amphibole. No trace of siderite has been found, nor have oölitic textures been observed, though conceivably they could have been destroyed during metamorphism, and it is postulated that the iron was precipitated directly as oxide or hydroxide and the silica as chert. Certain nodular structures (Figs. 8, 9) strongly suggest that the silica coalesced into balls and rolled around on the sea floor, picking up discrete oxide grains before burial. Such nodules are rare, however; most itabirite is finely laminated and must have been deposited by rhythmic alternations of iron-rich and silica- or in places carbonate-rich precipitates. Factors that controlled the development of hematite or magnetite must be related to variations in the original sediments, for their present-day distribution follows bedding planes and even thin laminae, in spite of the long history of metamorphism and weathering.

Some data on the bulk chemical and physical characteristics of the itabirite suggest the magnitude of the problem of its origin. Table 1 gives

TABLE 1.

WEIGHT-VOLUME RELATIONS OF SILICEOUS ITABIRITE.

Fe %	Weight %		Volume %		Sp. gr.
	Hematite	Quartz	Hematite	Quartz	
70	100	0	100	0	5.20
60	85.8	14.2	75.5	24.5	4.60
50	71.5	28.5	56.2	43.8	4.10
46.3	66.2	33.8	50.0	50.0	3.93
40	57.2	42.8	40.0	60.0	3.67
30	42.9	57.1	27.5	72.5	3.38
20	28.6	71.4	17.0	83.0	3.10
10	14.3	85.7	7.8	92.2	2.86
0	0	100	0	100	2.65

the theoretical relations of iron content, weight and volume proportions, and specific gravity of a quartz-hematite itabirite, assuming the specific gravity of 2.65 for quartz and 5.20 for hematite, with no pore space, hydration, or other minerals. Note that the disparity in specific volumes of the two minerals makes quartz appear very prominent relative to its actual weight percentage. Material that seems extremely siliceous and low in iron is in fact fairly iron-rich. Visual inspection of many underground exposures, combined with sampling and analyses, suggests that the overall iron content of the formation may be roughly 40 percent. Now, if itabirite was deposited uniformly to a thickness of 300 m over the area enclosed by present-day exposures, simple calculations indicate that the quantity of iron involved is on the order of 4.4×10^{12} tons, and of silica (ignoring the carbonate) about 4.75×10^{12} tons. (Data used: area, 10,000 km^2; thickness, 300 m; 40 percent iron; sp. gr., 3.67.) These figures are intended only to show the probable order of magnitude. The proportion of the silica that should be calculated as calcium-

FIG. 8. Nodular structures in itabirite. Light-colored material is finely granular quartz with a little specular hematite; dark is chiefly hematite. Thin quartz veinlets cut quartz and hematite. Coin 19 mm in diameter, same as American penny.

FIG. 9. The same specimen from the side; shows elongation of the nodular structure parallel to the regional lineation.

magnesium carbonate is not known, as surface leaching has removed much of it (see below, in section on weathering), but it seems significant that for much of the period of chemical precipitation the rate of carbonate deposition was not great enough to mask the iron and silica by its volume. In other words, conditions were not favorable for its precipitation.

James (23) has recently shown that there are four distinct mineralogic facies of iron formation in the Lake Superior district—the oxide, carbonate, silicate, and sulfide. The Brazilian itabirite clearly corresponds to the oxide facies. Krumbein and Garrels (25) have pointed out the chemical conditions of oxidation-reduction potential and acidity (Eh and pH) required to form each of these facies. For the oxide facies these are positive Eh and a pH between 7.0 and 7.8, considerably less alkaline than normal sea water. Numerous studies have shown that iron and silica can be transported either as colloids or in true solution, and that they will be precipitated soon after contact with sea water. Gruner (13) states that the Amazon River carries enough of these substances to produce the Biwabik formation in 176,000 years. Hence, even though the quantities involved stagger the imagination, their source is not the fundamental question. To the writer, the problem of the origin of the Precambrian iron formations (and younger ones that closely resemble them) resolves itself into two parts: 1) conditions that inhibited the precipitation of calcium and magnesium carbonate, which are normally present in concentration greater than that of iron and silica in natural waters; and 2) the relatively great proportion of iron to silica and other precipitates.

Iron and silica are constantly precipitated, as their very low concentration in sea water proves, but under ordinary conditions they are masked by the great volume of other chemical precipitates (chiefly carbonates) and clastics. To explain the high iron content of the formations it is not necessary to build up any noteworthy concentration in the waters of the basin, as is necessary for an evaporite, but only to exclude other materials from the sediments. Clastic traps that settle out coarser particles are easily postulated, though it seems probable that the surrounding lands were low and that the clastic load was small or non-existent. T. P. Thayer (oral communication) has noted that present-day rivers in Liberia apparently carry only products of chemical weathering. James (24) believes that the Lake Superior formations are related to the development of the Huronian geosyncline, and suggests that off-shore swells or island arcs produced closed or restricted basins. Krumbein and Garrels show that to inhibit the precipitation of calcium-magnesium carbonates the pH of the system must be maintained at or below 7.8, the "limestone fence." Water of normal marine open circulation has a pH of about 8; therefore a restricted environment is required. As river waters are commonly less alkaline than sea water, large volumes pouring into restricted basins would be expected to reduce the pH materially, and might bring it below the limestone fence. The writer notes the abundant association of volcanic rocks with many, though not all, of the iron formations of the world, however, and suggests that they played more than the passive role assigned to them by James. It is suggested that volcanic emanations aided in lowering the pH of the basins, thus inhibiting the precipitation of

carbonates. Whether they also contributed iron directly to the system, as has been suggested by various authors, cannot be stated. However, the great preponderance of iron formation in the Precambrian, taken together with the vast land areas that would have had to furnish the iron through a single river system, or at most through a few major streams, suggests to the writer that magmatic sources may have furnished not only acids but part of the iron and silica as well. Pettijohn (28) emphasizes that the cherty iron formation problem is closely allied to the chert problem, and cites Taliaferro to the effect that parts of the Franciscan chert are in reality lean siliceous iron formation. Thus, although the major problem is not restricted to the Precambrian, the high-iron cherts are so restricted with only a few exceptions, and the writer feels, without any firm convictions, that the difference between the older and the younger formations may have been due to contributions of magmatic iron, added to the terrigenous iron. On the other hand, no volcanic rocks are known to be associated with what is perhaps the most notable of the younger iron formations, the Band' Alta formation of early Paleozoic(?) age, which is exposed in and near Morro do Urucum, Mato Grosso (7).

The origin of the two ferriferous series of the Congonhas district is postulated to have been somewhat as follows: Sedimentation began with nearly iron-free sands and clays, laid down at the border of a slowly subsiding trough (geosyncline). During this time the adjacent land masses were worn down to a low peneplain, and the last clastic sediments were fine muds. Rising offshore swells cut off most or all of the circulation with the open sea, producing an isolated shallow basin. Iron, silica, and calcium and magnesium, plus minor quantities of other substances, were brought into this basin in great volume by moderately acid river waters, either as solutions or as stabilized colloids, or more probably both. The pH was reduced below 7.8, perhaps in part by the contribution of acids from volcanos in the offshore arc. Iron and silica were precipitated somewhat rhythmically, probably because of fluctuations in the volume of water added to the basin. Iron is less soluble in sea water than silica, therefore it is to be expected that it would be precipitated more rapidly and sink more rapidly because of its greater density or tendency to a coarser flocculation, leaving the silica to settle more slowly. (The writer suggests that experiments could be devised to measure the actual rate of settling of mixtures of the two substances, and thus test the validity of this proposal.) The laminae may represent annual accumulations; if so, the length of time required for the deposition of the formation can be estimated. Measurements of various itabirite specimens show an average of about 10 laminae per centimeter, or, extrapolating, 1,000 per meter. Hence 300,000 years would be required to produce the formation if its average thickness is 300 m. This is of the same order of magnitude as the 176,000 years mentioned by Gruner for the Amazon to transport the iron contained in the Biwabik formation.

From time to time the pH crossed the limestone fence, and carbonates were precipitated. The presence of dolomite throughout the itabirite section at Passagem, as reported by Guimarães (19), suggests that there the alkalinity hovered close to 7.8 throughout the period of deposition. When the waters

were moderately oxidizing only hematite and silica were precipitated, and no organic material accumulated; but when the pH rose to 7.8 or more, probably because of the temporary incursion of sea water or reduced acidity of the streams, or perhaps because of lessened volcanic activity, the Eh fell and some organic matter was incorporated with the sediments. The stability diagram of hematite, siderite, and pyrite by Krumbein and Garrels (25, p. 15) indicates that with increased pH hematite will still form under mildly reducing conditions. No magnetite field is shown, but diagenetic or early metamorphic changes could produce magnetite from hydroxides or hematite in the presence of organic matter. Such a reaction may explain the association of magnetite with dolomite, or there may be some special environment in which primary magnetite could be precipitated directly.

With a pronounced increase in pH the calcium and magnesium ions, held in solution and concentrated during the period of iron oxide-silica deposition, would be rapidly precipitated, producing the thick lenticular masses and extensive beds of dolomite. (The dolomite may be the result of later magnesian metasomatism of limestone.) Incomplete exposures suggest a gradational lower contact for at least some of the dolomites, with alternating iron- and carbonate-rich beds, succeeded by purer dolomite. In at least two places the pure dolomites are overlain by a meter or so of green chlorite schist containing extremely fine needles of rutile, and the chlorite schist is in turn overlain by normal itabirite. To the writer this suggests that a heavy ash fall terminated the carbonate precipitation and more acid conditions resulted from the volcanism.

During this period the trough subsided slowly. The lack of facies other than the oxide indicates shallow, well-aerated waters, and the very regular lamination shows that the waters were calm and not affected by severe oceanic storms. Barbosa (1) describes wave-ripple marks from Usina, at the eastern edge of the Congonhas district, but they are restricted to a few thin beds of ferruginous dolomite and have not been found elsewhere. The dolomite breccias were doubtless produced by storm action that stirred up the sediments on the shallow bottom, but dolomites were precipitated at times of more open circulation, when ocean storm waves could reach into the depositional basin. The angular character of the fragments shows that the silica hardened rather quickly.

The geosynclinal trough deepened at the close of the itabirite deposition, and began to fill with a mixture of terrigenous and pyroclastic sediments, and perhaps flows. The adjacent lands probably began to rise, for quartzites are fairly common in the area north of the transcurrent fault. Some are cross-bedded, indicating that the waters remained shallow, or even that the area was temporarily above sea level. Local isolated basins permitted recurrent itabirite deposition. South of the fault, in an area that may have been some distance away, deep subsidence occurred. Abundant sediments, perhaps in large part derived from the island arc, were "dumped in" to form the green schist-graywacke-tuff sequence, with very little iron formation and no quartzite.

There is no evidence in the Congonhas district to show how long the break may have been between the top of the Minas and the succeeding Itacolumi, or,

indeed, if there was any real break, as the uplift of the border of the geosyncline suggested for upper Minas time may have continued, intensified, and migrated toward the axis of the trough. At any rate the Minas was being eroded before severe folding occurred, as the nearly undeformed itabirite pebbles in the conglomerates demonstrate. Rapid deposition of more or less unsorted Minas debris took place. Locally, however, conditions of chemical precipitation recurred. This is of particular interest, for these iron formations of the Itacolumí series are interbedded with quartzites and breccia conglomerates that prove that the conditions for iron precipitation were not at all critical during the Precambrian. Iron could be precipitated more or less "at the drop of a hat."

Many pebbles in the conglomerates are red jasper or very fine grained white "chert," quite different from the granular itabirite. It is probable that the iron formation of the Minas series had not been entirely altered to itabirite by Itacolumí time. The "chert nodules" of Figures 8 and 9 are from the iron formation of the Itacolumí series. They seem to have undergone less deformation than the older itabirite, perhaps because the load of superincumbent sediments was not so great.

THE HEMATITE DEPOSITS.

Description.

The hematite deposits of central Minas Gerais are masses of nearly pure specular hematite that so far as is known occur almost exclusively in the middle group of the Minas series. They range in size from thin lenses or beds in itabirite to bodies containing probably 100,000,000 tons or more, in length from a meter or so to more than a kilometer, and in thickness from centimeters to at least 300 m. In general their long dimensions are parallel to the bedding of the enclosing sedimentary rocks, and contacts are either sharp or sharply gradational to lower grade material. In places the contacts cut across the bedding, however. The most outstanding example of such cross cutting relationships seen by the author is at the Candú mine near Brumadinho, some 30 miles northwest of the Congonhas district, where several 10- to 20-cm veins of massive hematite cut almost at right angles across the bedding of siliceous itabirite.

The mineralogy of the ore is simple; the ore consists almost entirely of specular hematite in a mosaic of interlocking grains about 0.01 to 0.1 mm across that are without noticeable orientation. Magnetite is not uncommon, however, as some zones are more or less strongly attracted to the magnet, and in some ores octahedra from a millimeter to a centimeter across are visible to the naked eye (Fig. 10). In polished section these are seen to consist of martite, often with unaltered cores and fragments of magnetite, which preserve the original outlines of the magnetite crystals (Figs. 11, 12, 13). The hematite is coarsely crystalline, in contrast to the fine-textured groundmass. One or at most a few individuals replace the entire octahedron. Commonly the different quadrants of the section are composed of different individuals,

FIG. 10. "Martite" octahedra in fine-grained massive hematite. Numerous unreplaced magnetite remnants appear slightly darker than the coarse hematite. Polished face, × 1.

FIG. 11. Coarse-grained hematite after magnetite, surrounded by normal fine-grained, mosaic-textured hematite. XN, × 73.

as though replacement began at the corners of the octahedron; in some crystals replacement seems to have begun along the faces. A relatively rare type is that shown in Figure 12, where replacement was strictly controlled by the octahedral planes of the magnetite and the different individuals extinguish uniformly across the grain to give a three-directional grid pattern. A third

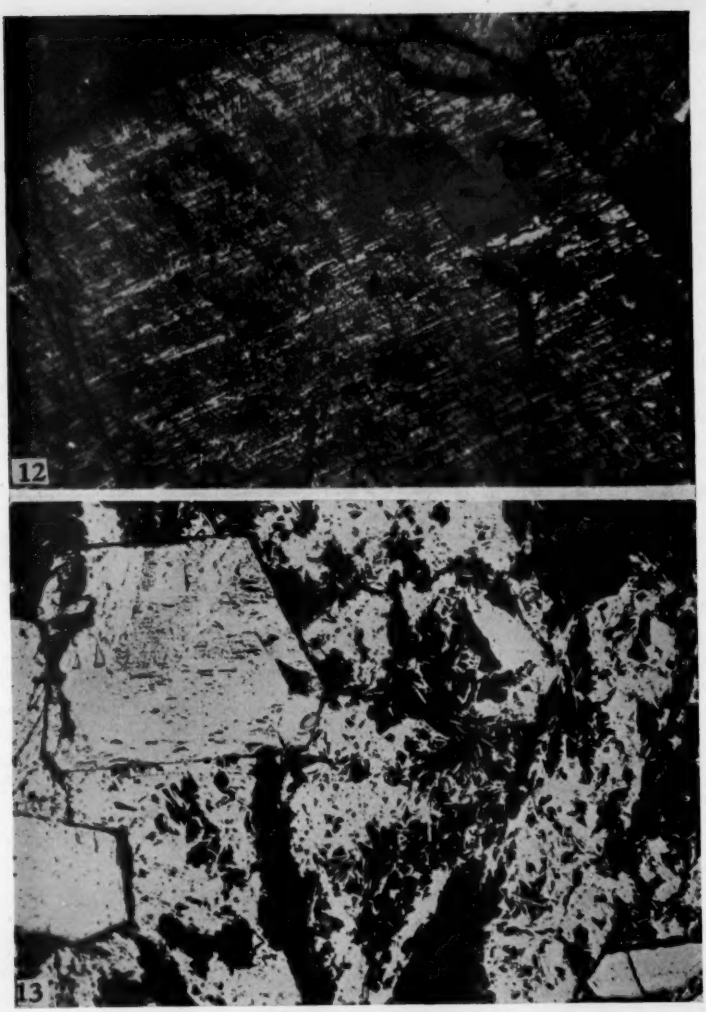


FIG. 12. Hematite that has replaced magnetite along the octahedral planes. The unlined gray area is unreplaced magnetite. XN, × 73.

FIG. 13. Martite with a few magnetite remnants, in matrix of fine hematite and platy hematite growing with random orientation. The black areas are hydrated hematite that pitted during polishing. Plane light, × 32.

crystal habit of the specularite is that of tabular plates 0.1 to 1 mm across that are also without orientation (Fig. 13).

The most common silicate is talc, as aggregates of minute grains and also as plates as much as several millimeters across. Its distribution is by no means uniform; some ores contain up to several percent, rather evenly distributed as aggregates more or less oriented in a planar fashion. Other ores have talc lining elongated open cavities or forming thin films, reminiscent of schlieren in igneous rocks. The greater part of the ore does not have any talc or other visible impurities.

Pyrophyllite in tiny radiating clusters of bladed crystals has been found in a few places, but it is extremely rare. Small white patches or blebs, which are apparently a kaolin type mineral after some unknown silicate, occur sparingly. Quartz grains are occasionally seen, but most ore does not contain visible quartz. Although itabirite has been described as grading imperceptibly into ore, there seems to be a definite break between itabirite with appreciable amounts of quartz distributed in laminae and the hematite ores with little or no quartz.

TABLE 2.

ANALYSES OF HEMATITE ORES FROM MINAS GERAIS.

	1	2	3	4	5
Fe	68.8%	67.10%	68.79%	68.87%	68.7%
SiO_2	0.2	0.43	0.37	0.30	0.52
Al_2O_3	—	1.20	0.17	—	—
P	0.005	0.087	0.046	0.07	0.036
H_2O	0.1	—	—	—	0.78

1. Sample from exploration adit, Casa de Pedra, Congonhas district. Analyzed by the D.N.P.M. laboratory, Rio de Janeiro.

2. Unweighted average of 81,485 tons of run-of-mine ore, destined for blast-furnace use, representing part of the Casa de Pedra production between July 1947 and January 1948. Analyzed by the Cia. Siderúrgica Nacional. Fe range from 66.14% to 67.51%.

3. Unweighted average of 6,115 tons of picked ore, destined for open-hearth use, representing part of the Casa de Pedra production from July 1947 to January 1948. Fe range from 68.38% to 69.06%.

4. Hematite from exploration adit, Fábrica, Congonhas district, quoted from Grosse (12).

5. Average of 380,000 tons produced at Cauê Peak, Itabira district, in 1948. Buyers' analyses. Quoted from Whitehead and Dorr (35).

Innumerable analyses show the high-grade character of the ore. Some typical ones, made in various laboratories, are given in Table 2.

Manganese is never present in more than traces in the hematite ores. Sulfur is not often determined, but when analyzed for usually runs 0.1 percent or less. Magnesia, lime, titanium, and other impurities have only rarely been determined and are in every case small or not present. The ores are not, perhaps, as uniform as analyses 1, 3, 4, and 5 would suggest, but they are of remarkably constant composition, approaching the theoretical value for pure hematite, 69.94 percent iron. Whitehead and Dorr cite one shipload that assayed 69.9 percent! Presumably this ore contained an appreciable amount of magnetite.

The specific gravity of the ore naturally varies somewhat with the porosity (see below under weathering). Measurements of several specimens of the better Casa de Pedra ore (the type represented by analysis 3 above) give values ranging from 5.12 to 5.19. Crystals from quartz veins range from 5.23 to 5.29, and two ores from elsewhere in the district gave 5.29 and 5.30. Determinations were made on fragments of perhaps 20 g each with the Jolly balance, and are believed to be accurate to 0.01. The differences probably have some significance. Purely qualitative tests with a magnetized needle indicate that the denser hematites have somewhat higher magnetic susceptibilities, but on the other hand they are also coarser-grained. It may be that the apparent lower density of the fine-grained ores is due to submicroscopic intergranular pore space, and the lower magnetism to the effect of random lattice orientation of the aggregates of minute grains in contrast to the uniform orientation of fragments of larger crystals.

Several distinct structures are present in the ores. Bedding is nearly always visible on weathered surfaces (Figs. 14 and 16) and on some polished faces (Fig. 15). In most places it is a thin, regular lamination like that of the itabirite; and, like the itabirite, it is commonly folded. Some ores are much thicker-bedded, however—from centimeters to perhaps a meter—so that individual blocks may show no sign of lamination, either on fresh or on weathered surfaces. These are the so-called massive ores. Figure 10 would illustrate this type were it not for the prominent martite crystals. Breccia structures are extremely common. Figure 17 shows the incipient stage of brecciation of a laminated ore. Note that some fragments have been moved considerably out of place and rotated. Figure 19 is of a specimen in which the bedding has been nearly destroyed. Other specimens, not illustrated, are virtually mylonites, although they may appear massive until examined on polished surfaces with reflected light. Figure 20 shows an unusual structure similar in appearance to the dolomite breccia conglomerate (Fig. 5). Angular, somewhat porous fragments and coarser-grained, partly rounded fragments, none showing any fine lamination, are set in typical massive ore. The entire mass is hematite. This structure has been found at only one place.

Under high magnification in reflected light none of these structures are visible; the ores are composed simply of the fine-textured hematite. It is noteworthy that the cleavage, apparently so prominent in hand specimen and on certain weathered outcrops (as in Fig. 16), is not determined in the Congonhas district by orientation of the specularite except in a few small deposits. These are thin beds in the itabirite of the uppermost thrust sheet that seems to have undergone the greatest stress, and presumably was transported the farthest. The specularite of the itabirite itself is much coarser-grained than the average for the district.

The linear structure so prominent in the area is expressed by the fold axes, elongated talc blebs, and a tendency for the ore to break in elongated blocks. A joint set roughly perpendicular to the lineation is especially well developed in the more massive ores. The longest dimensions of the deposits themselves apparently follow the lineation, and numerous observations indicate that the

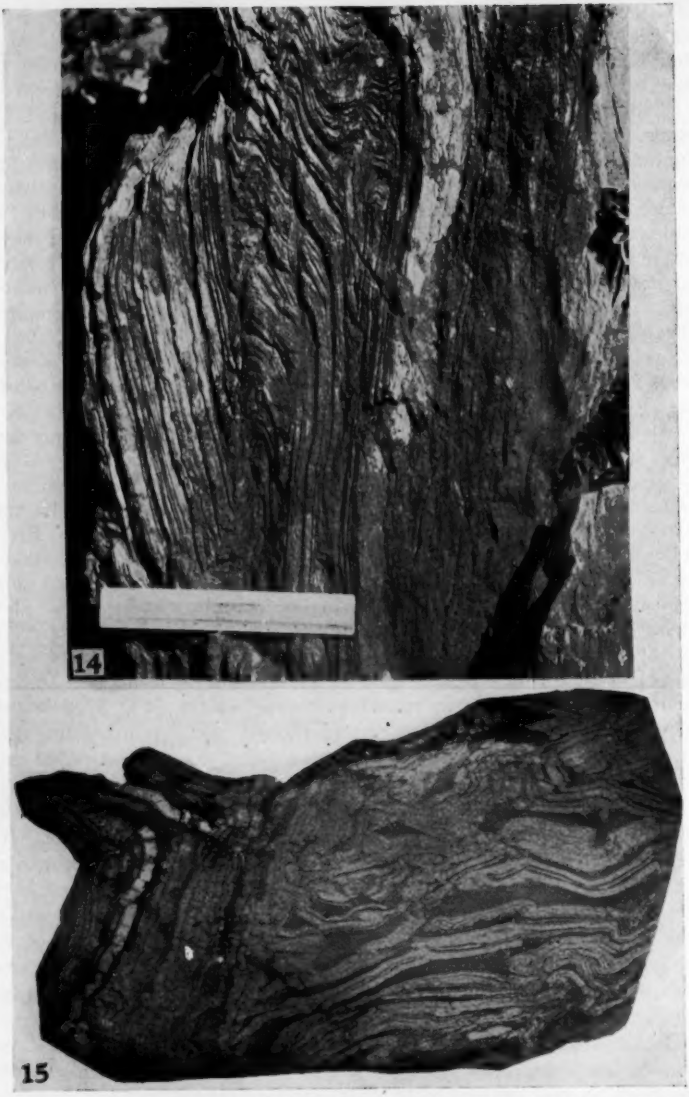


FIG. 14. Weathered face of hard hematite ore. Thin beds in middle were folded and somewhat sheared between more competent beds. Scale is 20 cm long.

FIG. 15. Thin-bedded, folded hard hematite ore. Specimen is entirely hematite, laminations visible because of microscopic differences in texture. Polished face, etched in cold HCl, reflected light. × 1.

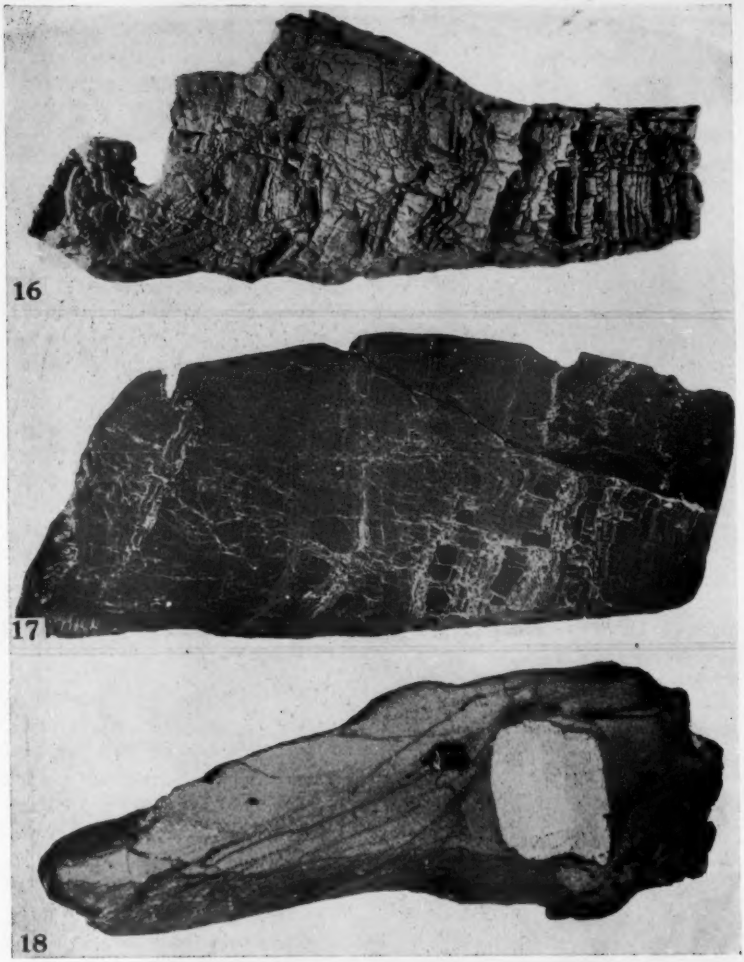
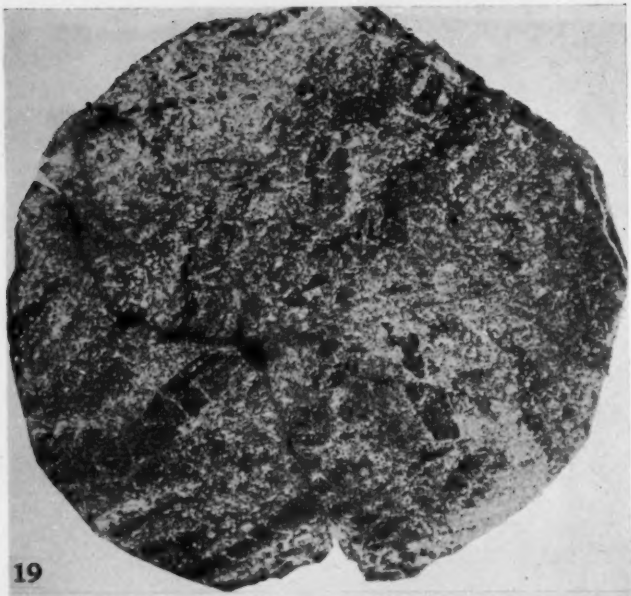


FIG. 16. Weathered face of hard hematite ore, showing bedding, relict cleavage, and incipient brecciation. × ¾.

FIG. 17. Polished, etched, and repolished face of same specimen as Figure 16, showing incipient brecciation preserved during replacement. All hematite, white is polishing powder filling crevices and pores opened by acid etch. × ¾.

FIG. 18. Fine-grained quartz fragment in hard hematite ore. Believed to be an unreplaced siliceous fragment from a dolomite breccia conglomerate. Sawed face, × 1.



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20

FIG. 19. Hard hematite with breccia structure that has almost destroyed the bedding of the original sediment. Polished specimen, reflected light, × 3.5.

FIG. 20. Hard hematite ore with structure of the dolomite breccia conglomerate (Fig. 5). Polished, etched face. The structure preserved by variations in the porosity of the ore.

best ores coincide with areas where the lineation plunges more steeply than the average.

The physical properties of the ores, which largely determine the use to which they are put and are thus of considerable economic importance, will be discussed in the section on weathering. For the present it can be stated simply that each type described occurs in all states from hard ore that rings under the hammer to soft incoherent powders that disaggregate between the fingers, although they preserve all the structures up to the moment of disaggregation. These differences are attributed to near-surface phenomena.

Origin.

The writer believes that most, if not all, of the hematite ore was formed by the metasomatic replacement of the silica and carbonate of the iron formation by hematite. Evidence for an epigenetic, rather than syngenetic, origin is of several kinds:

1) The martite clearly shows that hematite replaced pre-existing magnetite. Gruner (15, p. 641) states that "martite . . . seems to be of thermal origin in most cases," a statement with which the author agrees, for he has seen no evidence of alteration of magnetite to martite in the deeply weathered surface zone in Brazil. On the contrary, the surface materials seem to be somewhat more magnetic than the underlying ores, suggesting a certain amount of reduction.

2) The tight folds in much of the ore (Fig. 15) are similar to those in itabirite (Fig. 4), indicating that the two materials had similar competency at the time of deformation.

3) The hard ores could not have been contorted in their present state.

4) The very common breccia ores (Figs. 17 and 19) are completely healed. They record only a pre-existing structure that was replaced. Cleavages in rotated fragments have the same relation to the original bedding planes of the fragments, regardless of their orientation, indicating that the cleavage antedates the brecciation.

5) The structure shown in Figure 20 is that of the dolomite breccia conglomerate.

6) The fine-grained, unoriented texture of most of the ore indicates that the ore crystallized without directional stress and that it has not been subjected to severe metamorphism since its formation. This lack of orientation contrasts with the orientation shown by euhedral specularite in some of the itabirite and in a few thin, high-grade and exceptionally dense beds in the uppermost thrust sheet that may have been syngenetic and thus subjected to metamorphism.

7) No hematite boulders have been found in the conglomerates of the Itacolumí series, although itabirite is common. Ore fragments are abundant in present-day streams draining iron formation areas. They resist abrasion and solution to a marked degree, being carried long distances from the outcrop. Their absence in the conglomerates indicates that hematite ores as we know them today did not exist in Itacolumí time.

8) A thin hematite bed in the Itacolumí preserves the structure of a conglomerate (Fig. 21). Rounded pebbles with the fine lamination of itabirite are enclosed in a matrix of hematite. The mass is now composed entirely of

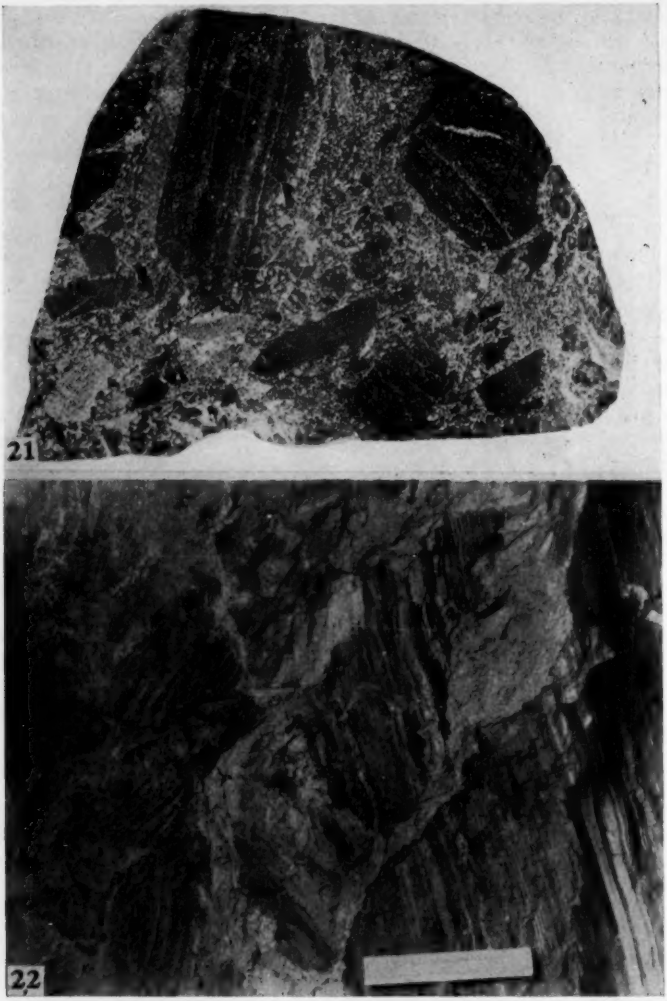

FIG. 21. Hard hematite ore with conglomerate structure, from the Itacolumí series. Both matrix and pebbles are hematite. Polished face, reflected light, × 2.
FIG. 22. Weathered dike cutting itabirite. Note that no replacement by hematite accompanied intrusion. Exploration adit, Fábrica. Scale is 20 cm long.

fine-textured specularite, except for a little pyrophyllite and a few coarse grains of quartz in the material interstitial to the pebbles. Near the pyrophyllite, partly replacing it and the quartz grains, the specularite has the coarser, unoriented platy texture.

9) One specimen contained an angular fragment of fine-grained quartz enclosed in hard hematite ore (Fig. 18). The texture and shape of the quartz fragment are identical with those of fragments in the dolomite breccia conglomerate, believed to be recrystallized from original chert. This specimen suggests that the siliceous fragment resisted attack by solutions that replaced the dolomite matrix.

10) Coarsely crystalline specularite occurs in a few quartz veins cutting Minas and Itacolumí rocks, proving that iron was mobile at least to some extent in post-Itacolumí time.

The following hypothesis is offered for the origin of the hematite deposits: The orogeny that thrust-faulted the Minas and Itacolumí series brecciated parts of the iron formation and the associated dolomites. Hydrothermal solutions of unknown source and character were introduced along faults. They spread out into the formation, particularly along the brecciated zones, replacing the silica and carbonate with specularite. Original bedding, breccia structures, and conglomerate structures were faithfully preserved by differences in texture of the specularite that, although inconspicuous on fresh surfaces and polished faces, are revealed by etching and differential resistance to weathering. Beds with a greater carbonate content were probably more susceptible to replacement; they form today the massive or thick-bedded ores. Thin-bedded itabirites were replaced by the thin-bedded, laminated ores. Magnetite, which had been crystallized into relatively coarse octahedra during the metamorphism accompanying the orogeny, was less susceptible to replacement. Its lattice structure controlled the hematite replacement to a marked degree. The talc present in many ores is believed to be residual from the dolomitic members of the formation. It is commonly associated with martite and seems to be more abundant in the massive ores believed derived from dolomitic beds than in the thin-bedded ores. (Talc is common in the surface zone of leaching and recementation; it apparently withstands all sorts of reactions that completely alter iron minerals.) The pyrophyllite is probably related to a late stage of hydrothermal activity. Solutions that deposited it may have caused some recrystallization of the hematite into the coarse plates. The quartz veins with the very coarse specularite plates belong to the latest hydrothermal stage, or perhaps are related to some more recent period.

Source of the ore-forming solutions.—The virtual restriction of the hematite ores to the middle group of the Minas series suggests that the iron was picked up from the itabirite formation itself and redistributed. Furthermore, the elements present in the ores are those found in the unenriched formation; no notable introduction of new constituents has taken place. The ratio of ore to the total volume of itabirite is so small that the abstraction of the necessary iron from other parts of the formation could not be detected. The agency that accomplished the concentration must have been heated waters.

Gruner's experiments (14) showed that the alteration of magnetite to martite proceeds quite rapidly in air at temperatures of 150° to 200° C but very slowly in water and various salt solutions at 100°. On the other hand, further experiments (16) showed that water or steam at temperatures of about 250° will oxidize magnetite readily, and such heated waters will dissolve relatively great quantities of silica, even in the form of quartz. Gilbert (11) expresses his conviction that hematite is nearly always hypogene and that platy (micaceous) hematite is never supergene. Butler's suggestion (4) that the products of dissociation of carbonate minerals in limestone contact zones will oxidize ferrous compounds to the ferric state may be pertinent, since the magnetite, originally associated with dolomite, has been largely oxidized to hematite, but his curve shows the optimum temperature to be 490°, and the unreplaced dolomite does not show evidence that it has undergone any such temperature. The temperature of the water was probably moderate.

Although the granodiorite stocks would seem to afford a likely source for the solutions, several facts argue against any genetic relationship between the ores and the intrusive bodies. A thin itabirite bed in the contact zone of the batholith at the north edge of the district was not enriched; on the contrary it is severely contorted quartz-magnetite schist, and presumably was reduced to magnetite, inasmuch as other quartzitic itabirite contains hematite.

Another line of reasoning involves the gold deposits of the area, which have not been mentioned in this paper until now. Native gold occurs in some hematite ores and itabirite, and formerly supported a flourishing mining industry. It also occurs in the contact zones of some granodiorite stocks, and in quartz-sulfide veins and lodes within the Minas series at a number of places in the area. At the Passagem mine a persistent bedding-plane vein follows the lower contact of the itabirite, but, although the formation is very dolomitic, no hematite ores were produced and the magnetite shows no sign of alteration to martite. The only apparent change was the development of pyroxene, glaucophane, cummingtonite, garnet, and tourmaline in the itabirite adjacent to the vein. The great Morro Velho deposit apparently consists of two parts—fissure filling of a vertical, east-trending zone and replacement of a folded carbonate-rich bed that was intersected by this fault. The vertical "main lode" is parallel to several faults of minor displacement in the Congonhas district that cut the thrust plates but have no apparent relation to the iron ore. This is considered as additional evidence, admittedly weak, that the hematite ores are not genetically related to the gold mineralization. The extremely low sulfur content of the ore also seems to deny any direct magmatic source for the hydrothermal solutions.

Investigation of the dikes that cut the ore and itabirite is greatly hampered by their extreme decomposition to all depths encountered in mining. Study of the heavy residues from a few dikes show tourmaline and zircon as the chief constituents other than iron oxides, which probably were picked up as inclusions. A zone of talc schist cut by a diamond-drill hole in the wall rock of the Casa de Pedra deposit may represent an ultramafic intrusive body. There are probably at least two dike types cutting the itabirite and ore, but fresh material will be needed before their characteristics and affinities can be

unraveled. The writer does not believe, from evidence that he has seen, that the dikes have a genetic relationship to the hematite ores, though some of them may well be related to the gold mineralization. Figure 22 shows a thin, anastomosing dike cutting itabirite in an exploration adit at the Fábrica property that has no spatial relationship to hematite ore.

The source and nature of the solutions is therefore a major problem. They may have been ground water, heated by deep circulation or by proximity to magmatic intrusions, as has been suggested by Gruner (17) for the Lake Superior ores, or perhaps connate water driven off from the sediments during their deep burial and metamorphism. Lateral secretion of solutions toward the fault zones, which would afford channels for their escape from pressure, may afford the most attractive hypothesis, for it would avoid the introduction of elements, such as sulfur, that are not present in the itabirite. It seems hard to explain how such solutions could be capable of leaching silica, however, as they should already be saturated with respect to it. Future investigations should provide an answer.

Distribution And Localization Of The Deposits.

Although the exact nature of the ore-forming processes is in doubt, mapping reveals a rather well established relationship between the deposits, faults, and carbonate-rich zones of the iron formation. The principal Casa de Pedra deposit, largest known ore body in the Congonhas district, lies between two overlapping thrust faults near their intersection with the upper, carbonate-rich part of the formation. No dolomite is exposed, but drilling proved the existence of dolomite weathering products in the wall rock. Several smaller deposits on the property are near known or probable faults. Casa de Pedra lies at the southwest corner of the ferriferous area, where east-west and north-south structures meet in a complicated zone of severely folded and faulted rocks. There is little reason to doubt that this complicated structure explains the number and size of the deposits found there. The Fábrica property a few miles to the northeast lies just east of the zone of major structural disturbance, but the formation is nevertheless considerably fractured. Most of the known hematite deposits occur on the flanks of an anticlinal structure in the upper part of the formation. They are isolated masses surrounded by dolomite weathering products. In the east edge of the district, around São Julião, no major faults cutting the iron formation have been found, and there is little hematite ore, but some minor bodies occur in the dolomitic zones.

That faulting was the major control and carbonate content secondary is shown by the areal distribution of hematite deposits elsewhere to the north and east. The Serra da Moeda, the north-trending western range that lies in normal succession on the gneiss, is not known to have any major faulting, and it contains no hematite deposits of any size. On the other hand the Serra do Curral, the northeast-trending range that extends with various names from a point near Itaú to and beyond Sabará, has a number of large deposits, and its structure is more complex. Near Belo Horizonte the stratigraphic section seems to be inverted, with south-dipping upper phyllites and perhaps Itacolumí

rocks overlying the granite and gneiss to the north. A long water tunnel driven through the range some 10 miles southwest of Belo Horizonte reveals intense deformation of the itabirite and suggests that at least one and perhaps more major thrust zones cut the range. Detailed mapping now in progress may show a relationship between the faults and the hematite ores. East of the Congonhas district the structure is apparently less complicated. Near Ouro Preto, the Minas and Itacolumi series dip south along the south flank of an anticline that plunges gently eastward. No major faults are known, and though the formation is unusually dolomitic (as revealed by exposures and drilling at the Passagem mine) no hematite ores are known.

Future mapping will reveal whether these general relationships can be extended into other parts of the ferriferous area.

Comparisons With Hematite Ores Of Other Areas.

The postulated hydrothermal origin of the hematite ores presents similarities with the genesis of ores from other districts of the world. Roberts and Bartley (29) suggest a hydrothermal origin for the hematite ore at Steep Rock Lake, Ontario, where solutions of magmatic origin are believed to have replaced brecciated dolomite. The same authors in a second paper (30) suggest that similar hydrothermal processes were responsible for the hard hematite ores of the Vermilion range in Minnesota and some of the Michigan iron ranges. In discussion of the first paper (29, p. 393–396), L. M. Scofield raises some objections to Roberts and Bartley's dating of the deposits and to their origin through the agency of magmatic solutions, suggesting that the replacement followed the severe post-Upper Huronian diastrophism and that it was related to circulation of heated ground water. This modified theory, if correct, would bring the origin of the Steep Rock Lake deposits into closer correlation with the hypothesis advanced in the present paper for the Congonhas deposits.

Burchard (2, 3) compared the ore of the Pao deposits, in eastern Venezuela, with those of Minas Gerais; but he emphasized features that indicated later enrichment, particularly the substitution of specularite for magnetite. As he followed Harder and Chamberlin in their theory of the syngenetic origin of the hematite of the Minas district, he was forced to postulate important differences for the origin of the Pao ore. It would seem that these supposed differences are smaller than was believed, though from his description it is apparent that the Venezuelan ores were formed at higher temperatures.

It has been proposed by de Villiers (33) that some South African hematite ores were formed by the metasomatic action of hydrothermal solutions, perhaps of mixed meteoric and magmatic origin, that leached iron and redeposited it in zones of brecciated iron formation close to dolomite. His photograph of a polished face of laminated, partly brecciated ore from the Thabazimbi area in the Transvaal shows that it is apparently identical to ore from the Casa de Pedra deposit. Even the general stratigraphic sequence, with the ferruginous conglomerates of the overlying Gamagara series, presents strong similarities to the Congonhas section. Professor Rudd of the University of

Adelaide writes (in a personal communication) that the Precambrian iron deposits in the Middleback Ranges of South Australia show evidence of structural control.

Thus there can be no doubt that the Brazilian ores do have very marked similarities to other hematites in many parts of the world, and the burden of proof of dissimilarity may rest with those who advocate other origins.

WEATHERING.

Deep weathering under tropical conditions has profoundly altered some of the rocks, making even their recognition difficult and producing changes that have significant economic importance. Most of the commercially valuable manganese deposits (27), for example, owe their concentration into marketable ores to surface oxidation, leaching, and redeposition. However, Derby (5) showed that the depth of this weathering, though great, is not unusual in comparison with depths reached by rock alteration elsewhere in nonglaciated parts of the world. The writer found that the depth of the weathered zone varied with the topographic setting, as would be expected. Itabirite is not fresh even in the center of the tunnel mentioned above, where, although it lies 220 m below the crest of the range, it is still an unknown distance above the water table. In less rugged terrane, drill holes near Congonhas reached firm rock (green schist) at depths of about 35 m on the ridges and 25 m in valleys. Some rocks, notably monomineralic ones such as quartzite, pure dolomite, and some hematite, are fresh at the surface.

Physiographic development naturally plays a part in any discussion of weathering, inasmuch as it controls the amount of time available for surface changes. The Minas Gerais iron area seems to have been emergent throughout much or all of the time since the late Precambrian(?) orogeny. Freyberg (8) considers that an extensive peneplain, remnants of which are seen in only a few of the highest ridges, was developed by Late Cretaceous or early Tertiary time. This surface has been raised by intermittent movement to its present altitude of some 6,000 feet, and was, of course, deeply dissected and nearly destroyed in the process. Terrestrial deposits containing a Miocene or Pliocene flora were deposited in a small basin about 1,500 feet below the remnants of the old peneplain at Gandarella, 20 miles north-northeast of the Congonhas district. They now dip about 20° east. Barbosa (1) distinguishes three levels of raised stream terraces near Congonhas, and the present-day streams are cutting into the Recent alluvium. Thus there is no question that the area has been rising for quite a while, apparently by block faulting with appreciable tilting. The deep dissection precludes any possibility that the hematite ores are related to the old erosion surface; and it indicates that near-surface chemical decomposition proceeds at a rapid rate to keep ahead of mechanical erosion.

Weathering Of Itabirite.

Weathering affects itabirite in two ways: 1) softening it where the principal action is solution and leaching of some of the constituents and 2) hardening it where hydration and cementation occur. In general the hydra-

tion and cementation are restricted to the surface zone and to open fractures; the great mass of the itabirite is more or less softened to considerable depths, and presumably to the water table. In places itabirite becomes so incoherent that it can literally be dug with the fingernails; elsewhere only the leaner beds are softened and the iron-rich beds remain partly or completely hard. Where these iron-rich beds are not cemented by limonite in the surface zone they give rise to "chapinha" ores. These are rubble ores made up of thin platy fragments of the richer beds remaining on the surface after the mechanical removal of the incoherent quartz grains of the more siliceous layers. Residual deposits of such material cover considerable areas to depths of several meters. As they are easily mined and screened of the enclosing soil and finer fragments by hand methods, and because the porous nature of the material makes it easily reducible in the charcoal blast furnace, chapinha ores are widely used by the domestic industry. They contain as much as 64 percent iron. At Casa de Pedra leached itabirite is being mined by power shovel and screened mechanically to give a product averaging about 62 percent iron. The process consists essentially of hastening the normal beneficiation by natural agencies. To treat itabirite in which both the silica and iron are disaggregated, some method of concentration based on the difference in specific gravities of quartz and hematite would be necessary. Tests have shown that Humphrey spirals will give a 67 to 69 percent iron product from such material (35).

The nature of this leaching is not understood. It must be some process that dissolves small quantities of material from the grain boundaries. Inasmuch as iron is more soluble in acid solutions, and silica in alkaline, the presence or absence of carbonates should play an important role in influencing the pH of the descending surface waters and hence the relative amounts of the substances leached. Thus differences in the original composition of the formation no doubt affect the amount and type of solution, and it seems logical to assume that the carbonate content of the itabirite was a controlling factor. In some areas where the leached material is highly magnetic it is obvious that removal of the carbonate has been the principal change, and laboratory experiments on leaching of a laminated magnetite-rich dolomite with weak acid yield duplicates of the chapinha ores. Where the iron is in the form of hematite and there is no evidence of pore space due to the removal of entire mineral grains, the former presence of appreciable amounts of dolomite is doubtful, however, and it seems more likely that the silica itself was partly dissolved. No evidence of slump and distortion of original structures has been observed; on the contrary the leached material preserves bedding, folds, and joints perfectly until disturbed by erosion or mining operations. This does not preclude an overall settling and compaction of the entire mass of leached material. Unfortunately there are no deep openings in the Congonhas district that go below the water table and afford an opportunity to study the itabirite in its fresh, unaltered condition. Certain very siliceous zones are fresh at the surface, but this fact alone marks them as atypical, and the fresh itabirite exposed in the Passagem mine contains various minerals introduced by the magmatic gold-bearing solutions and hence does not represent the normal rock.

A second type of alteration involves the hydration of the iron oxides to limonite. Quartz is almost entirely removed, the resulting pore space is largely filled with hard limonite, and the hematite itself is hydrated. This process commonly produces a resistant capping, almost an "armor plating," over the areas of itabirite outcrop that effectively protects the underlying zone of leaching. The cap is generally a few meters thick. On the tops of ridges and for some distance down the slope, the bedding and other structures are commonly preserved and the resulting material may be called "enriched itabirite." It is considerably less hydrous than common limonite, as the streak is ordinarily yellowish red and the iron content may be 65 percent or so. It may well be that the original hematite is only partly altered. The enriched itabirite grades downslope into canga, limonite cappings that consist entirely of transported material and hence do not show bedrock structures. Most canga contains more or less rubble of itabirite and, where hematite ores crop out up the slope, of ore fragments firmly cemented into a compact mass. The blanket gradually increases in thickness downslope, reaching as much as 10 m in places. It may extend out over formations other than the itabirite. With increasing distance from the iron formation outcrops, the canga becomes more porous and hydrated and contains fewer fragments.

Canga covers many square kilometers of the ferriferous area. The local industry uses considerable quantities of it because it is more amenable to treatment in charcoal furnaces than hematite. The iron content varies widely, according to the state of hydration and to the proportion of ore fragments and itabirite that it contains. The average may be 55 to 60 percent iron. The phosphorus content is always far higher than in the unaltered materials, going up to several tenths of a percent in places.

Accumulations of finely divided red hydrated iron oxide that is not cemented form the so-called laterite deposits. They are residual and transported soils containing more or less fragmental material from the iron formation and hematite deposits. With increasing clay content, as over phyllite areas, they grade into normal soils. In places the proportion of itabirite and ore fragments, and of limonite nodules similar to the "perdigones" in the Cuban laterites, is high enough to make the extraction and screening of the material profitable.

Topographic and perhaps climatic factors apparently determine if and where the limonite cementation takes place. Most canga cappings are being eroded at present; their remnants still cap the ranges, but erosion of the softer uncemented material undercuts them on the downslope side and produces nearly vertical cliffs. Some laterite accumulations in valleys and intermontane basins are being cemented, however, and presumably will be the future canga cappings. Remnants of canga sheets of several ages are left in the area; each sheet is no doubt related to a period of standstill and partial peneplanation of the region. In general the cappings are most extensively developed and best preserved on the slope toward which the formation dips, suggesting that downward-percolating solutions moved most readily along bedding planes, as would be expected. The iron was undoubtedly derived from the formation

by leaching. For some reason the silica was not redeposited; it was presumably carried away by ground water.

Weathering Of Hematite Ores.

The near-surface alterations of hematite ores are also of two sorts, leaching and cementation. Leaching is by far the more important. It attacks all types, but the thin laminated ores are the ones most affected. The process must be an intergranular solution that destroys the bond between the individual crystals, for the end result is a very fine incoherent powder of specular hematite. Some beds are commonly more leached than other adjacent beds, so that the thin-bedded ores are altered to material much like the chapinhas, in which harder laminae are separated by loose material that is hematite instead of quartz, as in the itabirite. The more massive ores ordinarily resist this leaching to a greater extent and may form hard ore beds and blocks surrounded by soft ore. According to the proportions of hard and soft material, and the relative remaining cohesion of partly leached hematite, the ores are classified as hard, intermediate, and soft. Structures are perfectly preserved, and as long as the soft ores remain damp they stand very well. Upon drying out, however, they fall to an almost impalpable, but very heavy, powder. Some ores are hard right to the surface, where they may crop out in bold escarpments or sharp peaks.

Angular blocks of the soft powdery hematite enclosed in clay below some outcrops show that this softening process is a present-day weathering phenomenon. The blocks could not have fallen in their present state without collapsing to powder. Furthermore, some of them grade inward imperceptibly from soft rims that can be scratched with the fingernail to cores of the hardest massive ore. The process is somehow related to moisture, for where the ore is continually wet, as in the blocks enclosed in clay or in low-lying deposits bathed in ground water, the softening is common. Exposures in a small prospect adit at Casa de Pedra demonstrate this softening process very well. A clayey laterite with numerous ore fragments is traversed by several hard, glassy-appearing limonite veins. Individual hematite fragments are hard and fresh where partly enclosed by the limonite but completely soft where they project into the uncemented laterite. Bold outcrops, intermittently wet by rains and then dried, show only a pitting on the surface where the rainwater stands; they are not otherwise affected. Hard ore fragments on the surface, or enclosed in canga, do not soften.

This softening process is not one of hydration, but of leaching of a small amount of hematite and incidentally of most of the impurities present, for analysis shows that the material left behind is nearly pure hematite. A sample from an exploration adit at Casa de Pedra, analyzed in the D.N.P.M. laboratory in Rio de Janeiro, gave 69.9 percent iron, 0.1 percent silica, 0.2 percent water, and no phosphorus or other constituents. One soft ore was very magnetic; it undoubtedly developed from a magnetite-bearing hard ore and shows that no oxidation accompanied the leaching.

The economic significance and importance of this weathering is obvious. If the softening is related to the present surface, as it seems to be, it should decrease downward and probably cease at the water table. Deep ores should be uniformly hard, and the vexing problem of what to do with the fines produced near the surface should gradually disappear as the depth of mining increases.

The surface zone over the softer laminated ore is ordinarily hydrated and cemented to a depth of a few meters, and limonite veins may follow cracks downward from the surface for considerable distances. The process is in every way analogous to the formation of canga. This limonitic material has a high phosphorus content, and care must be taken to exclude it from the highest grade ores during mining operations.

SUMMARY.

It is proposed that the Congonhas iron deposits resulted from the following geologic processes:

1) Chemical precipitation of iron oxide, silica, and calcium-magnesium carbonate in a shallow geosynclinal basin at least partly cut off from normal marine open circulation. Carbonate precipitation was inhibited during much of the period of deposition by a relatively low pH, possibly due in part to volcanic emanations from the rising offshore arc.

2) Regional metamorphism of the chemical precipitates to itabirite, a laminated iron oxide-quartz-dolomite rock.

3) Diastrophism, thrusting, and brecciation of the iron formation.

4) Hydrothermal leaching of the formation and metasomatic replacement of structurally and chemically favorable zones by specular hematite.

5) Near-surface leaching of the iron formation to produce soft itabirite, and cementation to produce enriched itabirite and canga.

6) Near-surface leaching of hematite deposits to form intermediate and soft ores.

The iron formation corresponds to James's oxide facies. The writer differs from James in assigning an active role to the volcanism. He allies himself with the "hot water" as opposed to the "cold water" school to explain the replacement hematite deposits, but he doubts that the solutions were contributed directly from magmatic sources. The Congonhas deposits have many similarities to iron formations and hematite ores in other parts of the world.

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ULVÖSPINEL AND ITS SIGNIFICANCE IN TITANIFEROUS IRON ORES.

PAUL RAMDOHR.*

ABSTRACT.

"Ulvöspinel," predominantly Fe_2TiO_4, is a widely distributed constituent of the magnetite fraction of magmatic ore segregations. Its presence can reduce considerably the amount of recoverable titanium. The identification of the mineral under the microscope is difficult. Methods of identification and types of intergrowths of the mineral are discussed.

INTRODUCTION.

V. M. GOLDSCHMIDT (1),[1] in the course of the stimulating researches in geochemistry, produced artificially the "spinel" Fe_2TiO_4, and pointed out the great similarity between the lattice constants and many of the other properties of this compound and those of magnetite. His work was briefly continued by Foslie (2), who mentions Fe_2TiO_4 as the possible titanium bearing constituent of some magnetites.

However, these observations were regarded by most investigators, including the present author, to be irrelevant in explaining the phenomena observed in naturally occurring magnetites; on the one hand neither of the papers mentioned above contains microscopic observations, and on the other hand it was not possible to harmonize these views with the well established observation that ilmenite is the titanium-bearing mineral in titanomagnetite. It was only later that the author (3, 4) found that many magnetites that crystallized at high temperatures in acidic and particularly in basic rocks, and which contain large quantities of $FeTiO_3$ (ca. 50%), show exsolution lamellae (100) rather than the normal ilmenite lamellae parallel to (111). The author showed that the lamellae parallel to (100) are particularly well developed and probably have the composition Fe_2TiO_4.

Finally Mogensen (5) was able to prove by means of X-ray diffraction studies that such exsolution nets consist predominantly of Fe_2TiO_4 in the relatively coarsely exsolved ores of Södra Ulvö. The slight discrepancies between the observed and predicted dimensions of the unit cell of the Södra Ulvö material are not surprising in view of the probable presence of MgO, Al_2O_3, and V_2O_3 in the structure. Anticipating the results presented below, it can be said that this might be expected on the basis of the somewhat variable reflectivity that has been observed in the material. This paper will follow the nomenclature of Mogensen (5) and will denote as ulvöspinel, Fe_2TiO_4 and mixtures of similar chemical composition.

* Translated from the German by Heinrich D. Holland, Princeton University.

[1] Numbers in parantheses refer to Bibliography at end of paper.

In the meantime the author (6) has called attention to the wide distribution of ulvöspinel in his book on ore minerals, and Hjelmquist (7) has published a more detailed description accompanied by excellent illustrations of a single occurrence. Thus, since ulvöspinel is much more common than was previously suspected, since it is a mineral which, without detailed instructions, can easily be missed in microscopic examination, and finally since it can be a disturbing factor in the dressing of titaniferous iron ores, a number of observations concerning its occurrence and properties are here presented.

MATERIALS INVESTIGATED.

It was only 14 years ago that the author learned to identify ulvöspinel under the microscope, and only more recently still has its occurrence been systematically sought. However, at least twenty-five occurrences of ulvöspinel are now already known, and a reexamination of old polished sections would at least double this number. In addition to these, there are instances where microscopically ulvöspinel has not been observed, where however on paragenetic reasons it might be expected to be present if the ½ mu lower limit of recognition under the microscope were removed.

The following is a list of occurrences that are discussed below:

1. Bühl, near Kassel, Germany; basalt with native iron
2. Södra and Norra Ulvö, Sweden; "titanomagnetite" differentiate in gabbro
3. Taberg in Småland, Sweden; "titanomagnetite" differentiate in hyperite-gabbro
4. Kramsta near Järvsjo, Sweden; magnetite-ilmenite differentiate in hornblende gabbro (or basic diorite)
5. Alnö, Sweden; magnetite differentiate in jacupirangite
6. Katschanar, Urals; apparently magnetite differentiate in gabbro
7. Denischkin Kamen, Urals; ditto
8. Bombiano near Bologna; normal gabbro
9. Magnet Heights and many similar occurrences in the Bushveld, Transvaal; magnetite bands in norite
10. Mooihoek, Transvaal; hortonolite pipe carrying platium
11. Vygenhoek, Transvaal; hortonolite rock containing scattered clusters of magnetite crystals
12. Leeuwfontein near Pretoria, Transvaal; jacupirangite
13. Spitskop near Middelburg, Transvaal; contact metasomatic titanomagnetite in the elaeolitesyenite region
14. Doros, Southwest Africa; alkalized portion of karroo dolerite ("core diabase")
15. Chinjumba, Gambos, Chitada and Chihanji, Angola; coarse titanomagnetite differentiates of considerable size
16. Blue Mountains, Virginia; magnetite differentiate in gabbro(?)
17. Essex Co., New York; titanomagnetite differentiate in gabbro

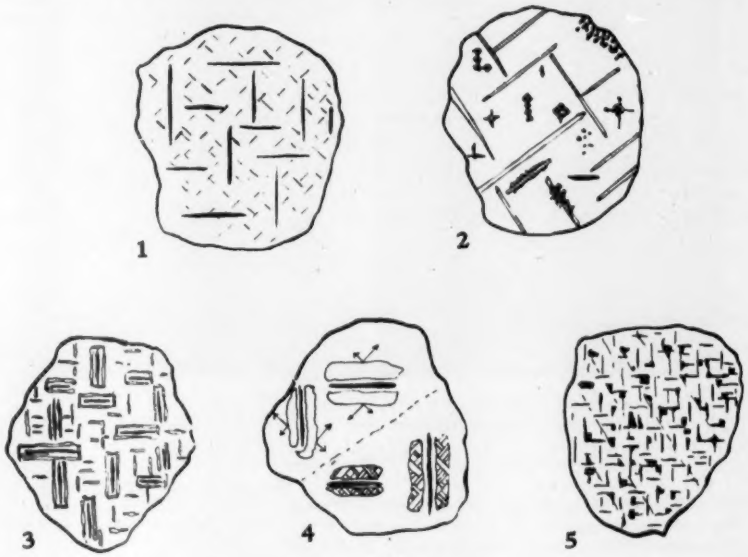
On the basis of this compilation alone it is apparent that differentiates from intermediate and acidic rocks are of minor importance only, and that in all the paragenetic relations FeO predominates over Fe_2O_3. These impressions are strengthened if those occurrences that are only casually treated here are also taken into consideration. This agrees with the observation that titanomagnetite differentiates, the ilmenite of which carries exsolution lamellae of

hematite do not contain ulvöspinel. Such occurrences are in any case rather rare. The typical hematite exsolution discs are much more common in more or less pure ilmenite differentiates (Ekersund, St. Urbain, etc.). Nevertheless there are also typical titanomagnetites with ilmenite rich in hematite (Routivare in part, Sördalen). Some cases are known that are apparent exceptions to the above rule in that some ilmenite carries hematite even in the vicinity of ulvöspinel-bearing magnetite. However, on careful examination it can be shown that this hematite is a secondary product of the magnetite lamellae in magnetoilmenite; such lamellae are thin and platy with parallel sides, not in the form of pods, and also commonly show the checker board structure of "martite."

The excess of FeO that has been found in the analyses of some magnetites is surely due in most cases to the presence of ulvöspinel. As such it may replace Brun's (8) "iozite," naturally occurring FeO, which was postulated to account for the excess of this compound in magnetite analyses. At any rate it might be expected on the basis of the chemical analyses that such material should also contain a good deal of TiO_2, and that it be strongly magnetic, both of which are true for ulvöspinel and are not true for FeO.

OBSERVATIONS.

The observations made on ulvöspinel are illustrated by line drawings. The relationship between ilmenite exsolution and ulvöspinel exsolution in magnetite



FIGS. 1–5.

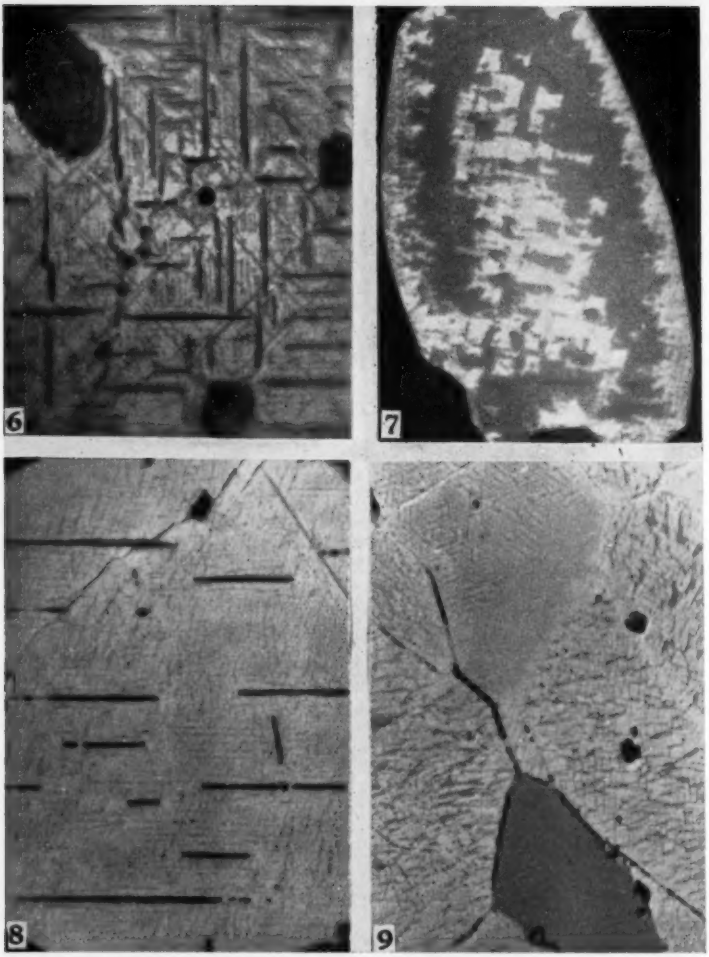


FIG. 6. Smålands Taberg, Sweden. Section // (100); (100)-lamellae of "pleonaste" with parallel lamellae of usp. and diagonal (111)-lamellae of idioblastically invading ilmenite. × 600. Note: the round spot in the upper right is a platy pleonaste lamellae parallel to the plane of the section.

FIG. 7. Vygenhoek, Bushveld, Transvaal. "Magnetite" as an inclusion in hortonolite. The magnetite actually consists mainly of usp. (somewhat darker). The sample containing the largest quantity of usp. in a plutonic rock! × 3,500 (remagnification of × 1,000 picture), oil immersion.

FIG. 8. Magnet Heights, Bushveld, Transvaal. Usp. // (100) and pleonaste

is best shown in sections parallel to the cube face (100). Such faces are in most cases easily recognizable since the exsolution lamellae of the usual transparent spinel (pleonaste) appear on them as two sets of long, thin, mutually perpendicular spikes (Fig. 6).

Figure 1.—In the common case of ilmenite exsolution as for instance in the Taberg ores, the (100)-lamellae of (Mg, Fe^{II}) (Al, Fe^{III})$_3O_4$ are relatively large and appear almost black under an oil-immersion objective; the ilmenite lamellae parallel to (111) make an angle of 45° with this set. They are mostly thinner than the spinel lamellae, although in some cases lamellae thicker than these are present either individually or throughout a section. Magnetite, which in some instances makes up no more than 50 percent of the section, fills the corners and interstices. If the fraction of magnetite is small, and the percentage of ilmenite high, in an exsolved mixed crystal, then the quantity of coarse-grained, and commonly that of recoverable, ilmenite is generally small, and vice versa. The former situation is found in specimens formed at elevated temperatures; however, the presence of other elements is also of importance in determining the coarseness of the exsolution structures.

Figure 2.—If the concentration of transparent spinel is small, or if such spinel is present as rather large irregularly distributed grains, or in a still different form as a border around ilmenite lamellae, or occurring in myrmekitic masses at grain boundaries, then the position of the ilmenite exsolution lamellae must be used to determine the orientation of the section. Under these conditions the ilmenite lamellae are mostly so coarse, that their optical orientation can be readily determined.

Figure 3.—The pattern of sections containing ulvöspinel is quite different. The (Mg, Fe^{II}) (Al, Fe^{III})$_2O_4$ lamellae are commonly similar to those in Figure 2, although they may be thinner in cross section and fewer in number, which corroborates other evidence that normal spinel is present in solid solution in ulvöspinel. Surrounding the spinel lamellae, but generally separated from them by a thin layer of magnetite, the ulvöspinel lamellae are arranged either in complete box-like structures or parallel to the elongation of the spinel lamellae. In addition there are numerous smaller and thinner ulvöspinel lamellae not visibly related to the spinel lamellae. This type of section is most easily recognized, for the ulvöspinel lamellae enveloping the spinel tend to be relatively coarse, so that the absence of anisotropy is recognizable, and their orientation is conspicuous as in Figure 8. Color is not a safe criterion for distinguishing ulvöspinel from ilmenite. The color of both varies slightly (as does that of magnetite) due, for instance, to differences in MgO content, so that the color of the minerals overlap. On the whole the reflectivity of ulvöspinel is somewhat less than that of ilmenite.

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lamellae // (100) partially boxed in by usp.; major constituents: magnetite. × 1,000, oil immersion.

FIG. 9. Chihanji, Angola. Titanomagnetite differentiate recrystallized at very high temperature. A grain of ilmenite (dark gray, homogeneous), magnetite grains in various orientations with (100)-net of usp. (the triangular pattern results from a cut parallel to the octahedral planes). × 1,100 (remagnification of × 600 picture), oil immersion.

Figure 4.—Commonly, however, the above arrangement persists even after Fe_2TiO_4 has been destroyed by oxidation:

$$3Fe_2TiO_4 + O = 3FeTiO_3 + Fe_3O_4$$

In this case there is of course the question whether the $FeTiO_3$ originated in this manner or through direct unmixing. However, a determination of the extinction direction of the lamellae serves to answer this question. It is not always possible to carry out such a determination since observations at very high magnification require strong depolarization. Where such measurements can be made, the $FeTiO_3$ lamellae formed by oxidation extinguish obliquely[2] as in the upper left of Figure 4; this is in contrast to the parallel extinction of

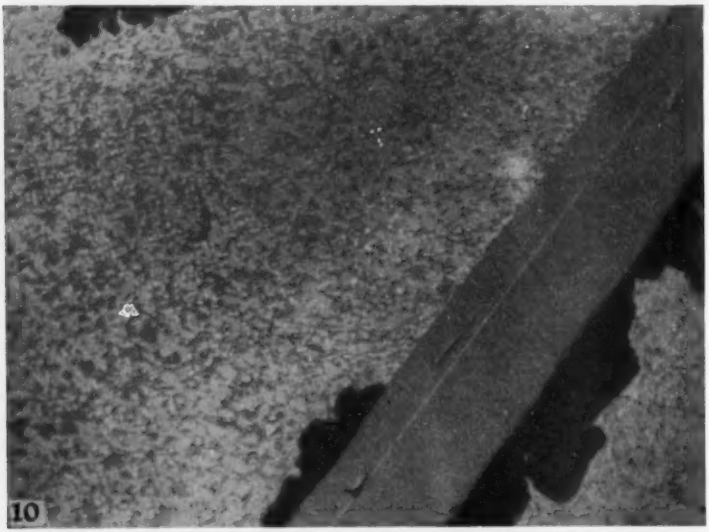
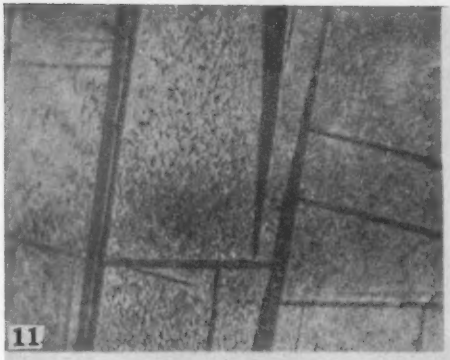


FIG. 10. Chitado, Angola. Usp. present to almost the same extent as magnetite. A thick, early lamella of ilmenite partially surrounded by pleonaste (almost black). In the neighborhood of ilmenite lamellae the magnetite is somewhat lighter due to the initiation of maghemite formation. × 1,200 (remagnification of × 600 picture), oil immersion.

lamellae formed by direct exsolution. It can be seen that despite differences in shape and orientation, both sets of lamellae extinguish in the same crystallographic direction. An unequivocal answer to the question of the origin of the ilmenite can be obtained when the $FeTiO_3$ formed by oxidation of the ulvöspinel forms a parquet of extremely small, short "sublamellae."

[2] Possible exceptions: a few instances in specimens from Kramsta.



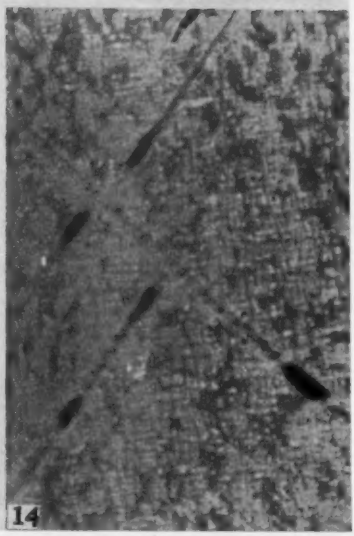


FIG. 11. Doros, Kaokoveld, Southwest Africa. Magnetite from "core diabase." Coarse exsolution of ilmenite // (111). Irregular network of small amount of usp. in magnetite. × 1,000, oil immersion.

FIG. 12. Essex Co., New York. Usp. next to a lamella of pleonaste in magnetite (section approximately // (111)) which in turn is coarsely exsolved in a spinel of a titanomagnetite rock. × 1,000, oil immersion.

FIG. 13. Smålands, Taberg. See description of Figure 6. × 1,050 (magnification of section of Figure 6).

FIG. 14. Gambos, Angola. Fine grained (100) network of usp. with magnetite. Diagonal idioblastic lamellae of ilmenite // (111) which is here accompanied by spinel. × 1,800 (remagnification of × 600 picture), oil immersion.

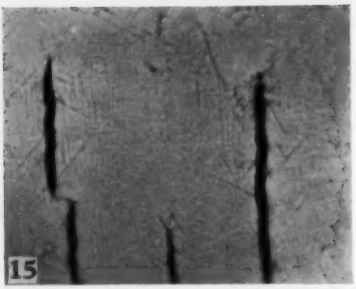


FIG. 15. Essex Co., New York. Usp. // (100) next to pleonaste // (100). Diagonal ilmenite with pleonaste lamellae as points of departure, indicating that ilmenite is younger (cut not exactly parallel to the cube faces). × 1,000, oil immersion.

The recognition of this feature requires practice and a particularly coarse development of the lamellae. It can also be shown that at times these lamellae, and also the "sublamellae," are older than invading ilmenite lamellae parallel to (111) (see below). On the other hand, lamellae of ilmenite and ulvöspinel have been observed to be almost simultaneous, which is to be expected for certain values of the $FeO:Fe_2O_3$ ratio.

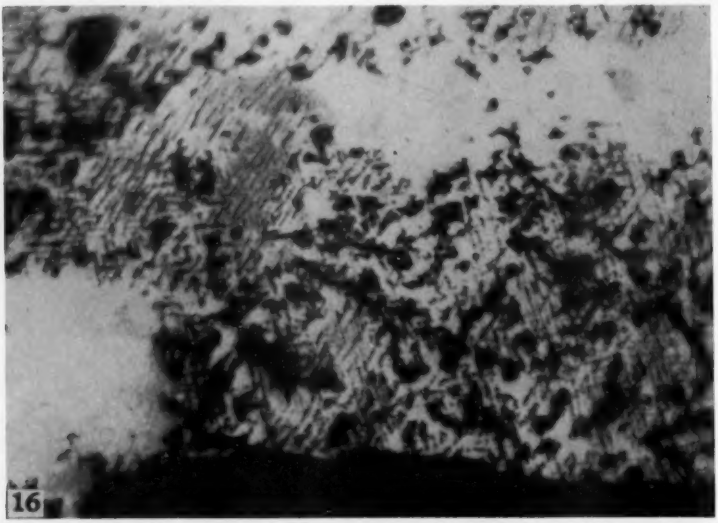


FIG. 16. Spitskop near Middelburg, Transvaal. Exsolved usp. has been selectively dissolved out of magnetite. In "healthy" magnetite there are in some places remains of usp.; these are slightly darker than the magnetite. × 2,500 (remagnification of × 1,000 picture), oil immersion.

Figure 5.—A final and very common type generally carries no spinel or has spinel present in separate masses that are generally coarse, rounded, and, in some cases, branched. The ulvöspinel makes up a network of thin lamellae that is uniform throughout the specimen when the ulvöspinel content is small. Where the amount of ulvöspinel is larger, the position of the lamellae becomes

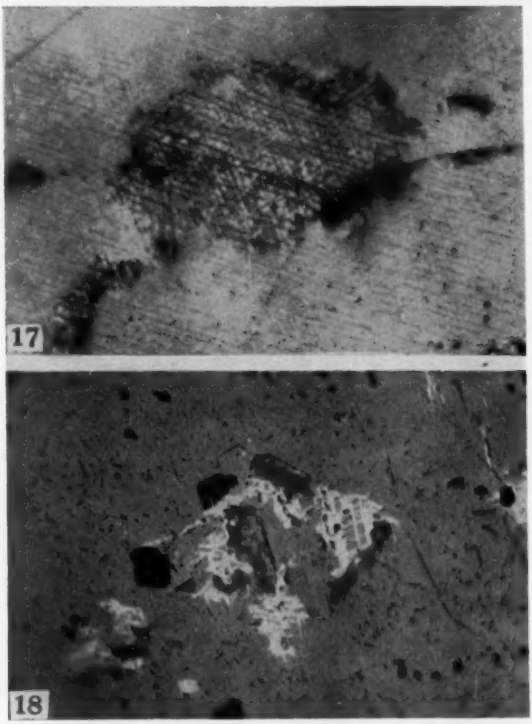


FIG. 17. Leeuwfontein, eastern Pretoria, Transvaal. Exsolved usp. selectively dissolved out of the magnetite. In the main the usp. network is easily recognizable.

FIG. 18. Spitskop near Middelburg, Transvaal. Magnetite which is conspicuously dark due to the presence of extremely thin usp. lamellae. Locally and in recognizable connection with cracks or grain boundaries a partial oxidation leading to the formation of ilmenite and magnetite betrays the presences of usp., which would otherwise have been overlooked.

more random, particularly where all three systems intersect. Locally it may then appear that ulvöspinel is the parent substance and that magnetite is the constituent of the exsolution net. Star-like and box-like forms may also develop from this type (Figs. 7, 9, 10, 12).

In all the types in which ulvöspinel is present (Figs. 3, 4, 5) complications arise due to two causes. First, there is commonly, in addition to the spinel and ulvöspinel exsolution, the old and coarse exsolution of a relatively weakly reflecting and probably magnesium-rich ilmenite, as in Figures 10 and 11. Second, ilmenite lamellae grow idioblastically into the magnetite parallel to (111), most probably due to weak oxidation of the ulvöspinel at the conclusion of the rock forming process. This may take place quite systematically (Fig. 13), is most commonly localized by cracks and grain boundaries (Figs. 14, 15), but may be quite irregular and the result of influences that are at present unknown. All of these distributions are commonly to be found in a single polished section. Even the ilmenite lamellae of Figure 4 may be attacked and transformed to (111) lamellae.

In Figure 13, lamellae of pleonaste parallel to (100), of ulvöspinel parallel to (100), and idioblastic ilmenite lamellae parallel to (111) are all present.

In numerous instances and well illustrated in Figures 10 and 14 the presence of ulvöspinel causes the initiation of the growth of maghemite from magnetite without the destruction of the magnetite lattice. Ulvöspinel itself does not undergo this alteration; it remains unaltered for a brief period, and then may be transformed rapidly to a fine-grained aggregate of ilmenite by means of complete recrystallization.

IDENTIFICATION.

As mentioned above, the exsolution network of ulvöspinel is very easily overlooked; however the ease with which it is destroyed can sometimes serve as a criterion. Sometimes magnetites, which appear to be homogeneous even under rather high magnification, are found to contain solution patterns as shown in Figures 16 and 17, which point to the undestroyed intergrowth pattern of two very similar minerals. In such a situation, careful search will usually reveal the presence of unaltered ulvöspinel. The origin of such solution nets is not always clear. They are to be found as the result of superficial weathering and at greater depth where weathering can probably be excluded as a cause.

A further indication of the presence of ulvöspinel can be the occurrence in a titaniferous magnetite of a granular, rather fine mosaic of ilmenite and magnetite, evidently formed by simultaneous crystallization and for which there appears to be little compositional reason. A careful investigation will then show that the section (Fig. 18) consists of an extremely fine-grained intergrowth of magnetite and ulvöspinel, which has been recrystallized under weakly oxidizing conditions. However ulvöspinel is most easily recognized when the type shown in Figure 3, as described above, is present, in which the ulvöspinel frames the (100) lamellae of spinel. The ilmenite lamellae formed from ulvöspinel as in Figure 4 are generally much too small to enable any but an experienced observer with first class microscopic equipment to recognize their reflection pleochroism or anisotropy under crossed nicols. It is possible, however, to observe in places the extinction of parallel groups of lamellae with intense illumination at reduced openings of the aperture diaphragm. Under

these circumstances, which resemble but can hardly be confused with those due to extensive, very fine martitization, the suspicion is well founded that unaltered ulvöspinel is probably present nearby.

A final indication of the presence of ulvöspinel can be found in the presence of holes, and areas of holes, which are stubbornly persistent when polishing is not carried out with great care; such areas have the appearance of the grid of a halftone illustration as seen under a hand lens. These polishing blemishes are due partly to the solution phenomena mentioned above, and partially to pseudo cleavage caused by the difference in the contraction of magnetite and ulvöspinel. In the latter case the holes do not appear when extreme care is exercised in preparing the polished section, an instance where such care can be self defeating.

I would like to emphasize that ulvöspinel possesses many more peculiarities than have been described above, and that in this paper I have tried to assemble only those properties that appear most important at this time. A report (8) has already been given of an occurrence of ulvöspinel without magnetitic matrix, formed under extreme reducing conditions from ilmenite in an iron-rich basalt. This occurrence is more of theoretical interest, but is here mentioned for the sake of completeness.

THE EFFECT OF ULVÖSPINEL ON ORE DRESSING.

Since ulvöspinel is approximately as magnetic as magnetite, it will follow this mineral rather than ilmenite in magnetic separations. This results in the loss of titanium on the one hand, and in the presence of undesirable titanium on the other. The quantity of titanium thus "misdirected" cannot be predicted, but may be quite considerable as can be seen from Figures 7, 9 and 10. The normal thin ilmenite lamellae parallel to (111) behave of course in the same unpleasant manner. But these are easy to recognize under the microscope and semiquantitative estimates of their abundance can be made by means of planimetric methods; it is, therefore, possible to avoid ore bodies containing large quantities of such ilmenite. By contrast ulvöspinel and ilmenite derived from ulvöspinel remain difficult objects to identify even for an experienced observer. It is just in those intergrowths that have an excellent appearance (magnetite, ilmenite, spinel, grains all larger than ½ cm) that the magnetite has at times been found to contain as much as 30 percent of extremely fine grained ulvöspinel. The engineer who "cannot recover better than 50 percent of the chemically proven titanium, even with such coarse intergrowths," can expect to meet with grave disapproval which, on the basis of the above observation, may not be justified at all.

HEIDELBERG, GERMANY,
July 1, 1953.

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ORIGIN OF ALUNITE DEPOSITS AT PIDINGA, SOUTH AUSTRALIA.

D. KING.

ABSTRACT.

The alunite deposits are located in Tertiary clays that form the beds of saline lagoons at the eastern margin of the Nullarbor Plain, South Australia. The clay beds were derived by the weathering of Precambrian granitic gneisses, and accumulated along with the soluble products of rock decay in depressed areas in the gneissic basement rock. Alunite is present in the clays only in localized areas that are characterized at the surface by the presence of siliceous and ferruginous lateritic cappings. It is believed that the actual alunization of the clay took place in Late Pliocene when lateritization processes were operative over widespread areas in Australia.

The alunite occurs in close association with kaolinite, and laboratory studies have shown the probability that kaolinite was an intermediate stage in the breakdown of feldspar to alunite.

INTRODUCTION.

THE alunite occurs in dry saline lagoons adjacent to the Nullarbor Plain, in the western portion of South Australia. The largest of the known deposits is at Pidinga, where the original discovery was made by Dickinson (9)[1] in the company of the writer. These, and other similar lake deposits of alunitic clay in the Chandler District of Western Australia (11), are the only known sedimentary occurrences of the mineral.

In its natural state when wet, the clay is pale cream in color, plastic, and except for a notably higher density, closely resembles kaolin clay with which it is associated. Dried samples crumble to a fine white powder that are easily dispersed in water to form a milky suspension.

The reserves of alunite are large but insufficient to warrant the high cost of the necessary plant at the present time. Kaolinite and quartz are the chief impurities and a simple washing process would possibly improve the grade of the raw material should exploitation be deemed desirable.

GEOLOGY.

The lagoons that contain alunite have been excavated in a thin capping of Tertiary sediments overlying Precambrian rocks. The best exposures of the Tertiary beds, which are regarded as marginal deposits of the Nullarbor Plain Basin, are seen along the edge of the lagoons at Pidinga, at Chundie Swamp, Lake Tallacootra, Ifoulds Lake and lakes near Ooldea Mission (Fig. 1).

The general geology of the Pidinga lagoonal areas has been described in detail in a previous paper (16), and broader aspects of it are illustrated in the accompanying plan and section (Fig. 2).

[1] Numbers in parentheses refer to Bibliography at end of paper.

In some places the alunite has been found to occur as an alteration product in deeply weathered granitic rocks. However, the largest deposits are developed as locally alunitized zones in Lower Miocene (?) unfossiliferous lacustrine sediments comprising clay, with some sand and grit, which form the beds of the lagoons and are exposed in the lower levels of cliffs fringing the lagoons. These sediments are overlain by Middle Miocene fossiliferous limestone, and overlie and are interbedded with Oligocene (?) lignitic deposits.

The distribution of the alunitized zones in the sedimentary clay corresponds closely with that of lateritic cappings. In some areas where the limestone

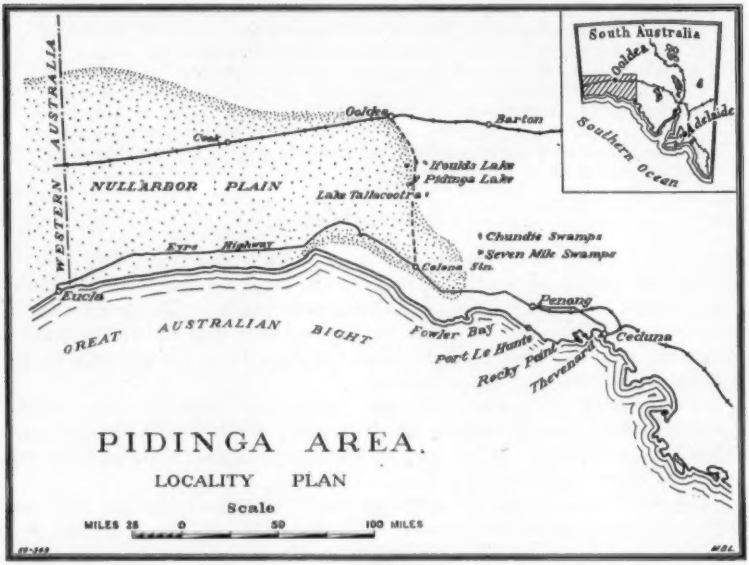

FIG. 1.

has been removed by erosion, the upper part of the clays are heavily stained and cemented with iron oxides and overlain by porcellanite. The assemblage of the three horizons characterized by the excess of kaolin, iron oxide and silica respectively may be regarded as comprising a true lateritic profile (22); the alunite is developed in the pallid zone of the kaolinitic clays.

In areas where the clay bed is overlain directly by fossiliferous limestone, lateritization effects are not marked, and alunite is generally absent, but the contact is featured by the abundance of selenite gypsum.

The association of alunite with laterite is not unusual, as alunite is known to occur beneath siliceous laterite cappings in other portions of South Australia, as for example in the breakaway country near Wynbring, and in the northern

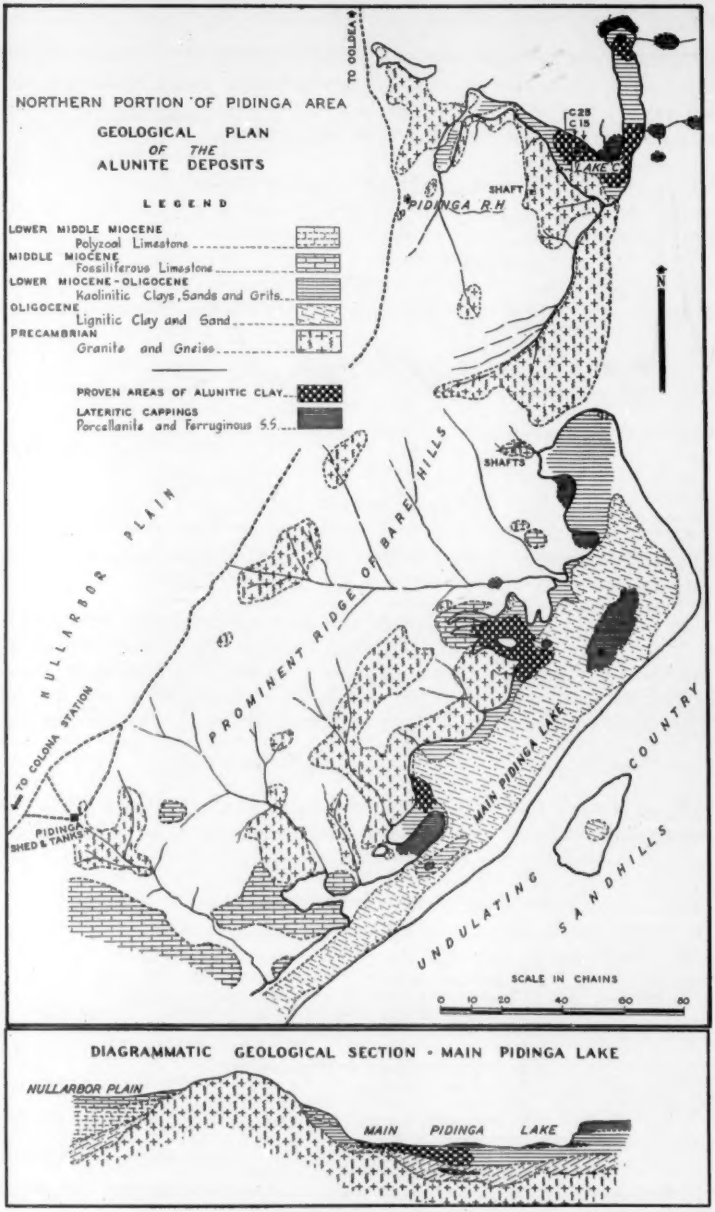
NORTHERN PORTION OF PIDINGA AREA
GEOLOGICAL PLAN
OF THE
ALUNITE DEPOSITS
LEGEND
LOWER MIDDLE MIOCENE
Polyzoal Limestone
MIDDLE MIOCENE
Fossiliferous Limestone
LOWER MIOCENE - OLIGOCENE
Kaolinitic Clays, Sands and Grits
OLIGOCENE
Lignitic Clay and Sand
PRECAMBRIAN
Granite and Gneiss
PROVEN AREAS OF ALUNITIC CLAY
LATERITIC CAPPINGS
Porcellanite and Ferruginous S.S.
TO OOLDEA
C25
C15
LAKE
SHAFT
PIDINGA R.H.
N
SHAFTS
NULLARBOR PLAIN
PROMINENT RIDGE OF BARE HILLS
TO COLONA STATION
PIDINGA SHED & TANKS
MAIN PIDINGA LAKE
UNDULATING SANDHILLS COUNTRY
SCALE IN CHAINS
0 10 20 40 60 80
DIAGRAMMATIC GEOLOGICAL SECTION - MAIN PIDINGA LAKE
NULLARBOR PLAIN
MAIN PIDINGA LAKE

FIG. 2.

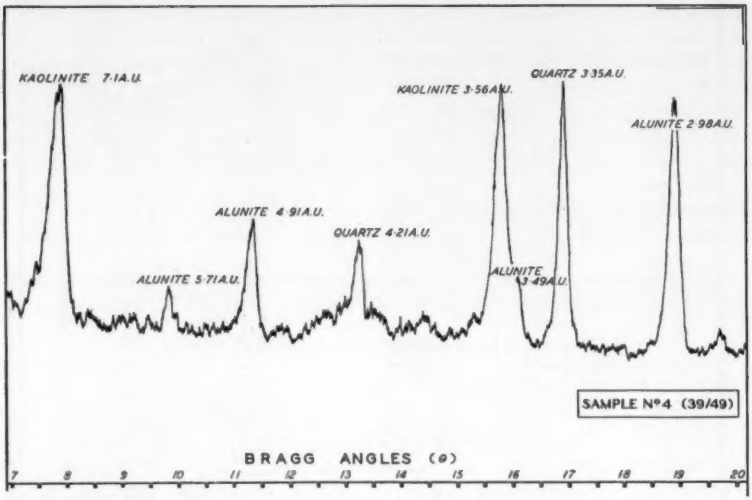

FIG. 3. Portion of an X-ray diffraction pattern showing major lines of alunite, kaolinite and quartz in Pidinga alunite sample.

Flinders Ranges (8). A similar type of association has also been noted at the Stuart's Range Opal Field (21), where the opal encloses nodules of alunite.

Evidence reported in a previous paper (16) indicates that the laterites of the Pidinga area were probably formed in the Pliocene period, and the excavation of the lagoons in the Tertiary sediments followed in the Pleistocene.

BOREHOLES.

Small areas of alunitic clay are known in the northern portion of the Main Pidinga Lake, but the most extensive occurrence is in an isolated lagoon

TABLE 1.

DETAILED LOG OF BORE C15, PIDINGA LAKE C.

Depths from surface, feet	Details of strata	Potash content, percent
0 – 0.08	Surface soil and drift.	
0.08– 5	Off-white gritty alunitic clay. Some selenite crystals.	7.64
5 – 8	Mottled cream and white slightly gritty alunitic clay. Some iron stains and selenite crystals.	6.20
8 –12	Mottled micaceous clay. White alunitic patches, iron stains, and black carbonaceous clay.	5.78
12 –20	Grey, gritty micaceous clay mottled with white alunitic clay.	3.40
20 –26.5	Mottled white (alunitic) and yellow (ochreous) micaceous clayey sand.	2.68
26.5 –39	Decomposed gneiss. White gritty clay, muscovite, and quartz with gneissic arrangement.	2.18
39 –40	Decomposed gneiss. White clay and some quartz.	6.90
40 –41.16	Decomposed gneiss. Mottled gritty clay.	0.64
41.16	Hard gneissic bedrock.	

known as Lake C. A number of boreholes were drilled on this lake by the South Australian Mines Department (1) to test the size of the deposit, and to obtain representative samples for analytical work. The alunitic clay bed was found to range in thickness up to 40 feet, depending on the depth to the gneiss bedrock.

The log of the deepest borehole (No. C15) is shown in Table 1 as a typical example of the exploratory boreholes drilled on Lake C, and the alunite content of each sample is indicated by the percentage of potash present. Full analyses of samples from this bore are shown in Table 2.

It is apparent from the analyses that the alunite content is very variable. The relation between grade and depth from surface is illustrated in the varia-

TABLE 2.

COMPLETE CHEMICAL ANALYSES OF ALUNITE SAMPLES FROM BOREHOLE C15, PIDINGA LAKE C.

Depth of sample.....	0–5	5–8	8–12	12–20	20–26½	26½–39	39–40	40–41
Reference No.....	33/49	34/49	35/49	39/49	40/49	41/49	191/49	192/49
Silica	9.92	19.00	22.40	33.76	37.08	35.20	13.62	63.76
Alumina	29.27	28.78	28.48	28.40	28.18	32.01	34.00	22.56
Ferric oxide	0.44	1.34	1.14	0.71	0.84	0.41	0.60	0.57
Magnesia	1.04	0.88	0.67	0.50	0.44	0.34	0.36	0.04
Lime	0.54	0.06	0.06	0.08	0.08	0.20	0.02	3.48
Soda	3.80	4.16	3.68	2.74	1.62	1.92	2.87	3.10
Potash	7.64	6.20	5.78	3.40	2.68	2.18	6.90	0.64
Water at 100° C	2.69	2.20	1.90	3.25	1.64	2.74	2.71	0.99
Water above 100° C	12.06	10.90	9.60	9.79	10.26	11.88	13.62	1.35
Titanium dioxide	0.05	0.06	0.28	0.49	0.90	0.64	0.08	0.99
Sulphur trioxide	30.11	23.87	23.79	13.72	14.28	10.34	23.92	1.76
Chlorine	3.67	4.06	3.44	3.55	2.62	2.91	1.98	0.72
	101.23	101.51	101.22	100.39	100.62	100.77	100.68	99.96
Less oxygen equivalent to chlorine	0.83	0.92	0.78	0.80	0.59	0.66	0.45	0.16
Totals	100.40	100.59	100.44	99.59	100.03	100.11	100.23	99.80

tion diagram (Fig. 4) showing the potash contents of samples from Bores C15 and C25, and indicates a general enrichment in alunite nearer the surface.

Tonnage estimates of reserves, based on a density figure of 1.02 cubic yards/long ton (14), show that 250,000 tons are available in Lake C for open cut mining. The weighted average composition of the reserves is listed in Table 3; the average potash content is 7.49 percent. Overburden averages less than one foot in thickness.

PETROGRAPHY.

Petrographic studies of the alunite samples reveal that the mineral is contained in the bedded clays and decomposed gneisses as a cryptocrystalline aggregate, and is generally associated with well-developed crystals of kaolinite,

TABLE 3.

COMPLETE CHEMICAL ANALYSES OF ALUNITE AND KAOLIN CLAY SAMPLES (VARIOUS).

Details of sample	1. Pidinga Lake C (best grade)	2. Lake Tallacootra (best grade)	3. Chundie Swamps (best grade)	4. Pidinga Lake C (low grade)	5. Main Pidinga Lake (best grade)	6. Main Pidinga Lake (kaolin clay)	7. Lake Tallacootra (kaolin clay)	8. Lake Campion, West. Aust. (average grade)	9. Pidinga Lake C (average grade)	10. Pidinga Lake C (weighted average reserves)
Reference	64/49	488/49	487/49	39/49	3453	3545	3348	(6)	86/49	—
	percent	percent	percent	percent	percent	percent	percent	percent	percent	percent
Silica	6.18	9.44	5.20	33.76	5.62	45.08	44.22	19.78	16.96	22.48
Alumina	32.20	30.85	31.21	28.40	31.73	31.67	31.26	28.17	30.95	26.29
Ferric oxide	0.66	0.77	3.25	0.71	0.32	2.37	1.64	1.15	0.24	1.99
Magnesia	0.32	0.30	0.02	0.50	0.02	0.07	0.32	0.31	0.44	0.35
Lime	0.32	0.06	0.06	0.08	0.04	0.08	0.12	0.34	0.92	0.13
Soda	1.70	2.24	1.96	2.74	2.54	2.82	1.56	2.56	2.72	0.46
Potash	9.50	9.02	9.20	3.40	9.28	0.28	0.30	7.49	7.60	7.68
Water at 100° C	0.82	1.92	1.77	3.25	1.85	2.00	2.85	0.98	0.68	0.92
Water above 100° C	12.59	11.82	11.95	9.79	12.58	11.31	11.60	10.54	10.15	9.63
Titanium dioxide	0.30	0.04	0.06	0.49	0.11	0.94	1.32	0.24	0.69	0.19
Sulphur trioxide	34.36	31.90	33.72	13.72	33.51	1.46	0.92	27.65	27.19	26.87
Chlorine	1.74	2.78	2.15	3.55	2.92	3.04	4.85	1.95	1.84	n.d.
	100.69	101.14	100.55	100.39	100.54	101.19	100.96		100.38	
Less oxygen equivalent to chlorine	0.39	0.63	0.48	0.80	0.66	0.69	1.09		0.42	
Totals	100.30	100.51	100.07	99.59	99.88	100.50	99.87		99.96	

and rounded grains of detrital quartz. In some examples the kaolinite is partly or completely altered to crystalline products similar to the alunite, but the individuals are too small to resolve by microscope methods, and it cannot be determined whether all the cryptocrystalline material is of the same composition.

The following descriptions are typical of the sedimentary alunite clays and altered granitic bedrock from Pidinga.

Sample No. 9.—This sample was cut from the core of *average grade white alunite clay* from Borehole C25, Pidinga Lake C, at a depth of 9–13 feet. Its chemical composition is shown in Table 3.

Under the microscope, the base of the clay is a homogeneous matte, in which individual crystals cannot be discerned, and color varies from colorless

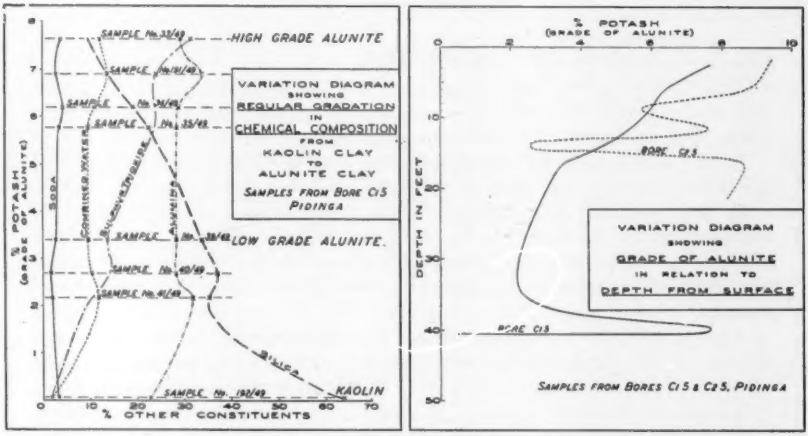
HIGH GRADE ALUNITE
LOW GRADE ALUNITE.
KAOLIN
VARIATION DIAGRAM SHOWING REGULAR GRADATION IN CHEMICAL COMPOSITION FROM KAOLIN CLAY TO ALUNITE CLAY
SAMPLES FROM BORE C15 PIDINGA
% POTASH (GRADE OF ALUNITE)
% OTHER CONSTITUENTS
DEPTH IN FEET
VARIATION DIAGRAM SHOWING GRADE OF ALUNITE IN RELATION TO DEPTH FROM SURFACE
SAMPLES FROM BORES C15 & C25, PIDINGA

FIG. 4. Variation Diagrams.

to pale grey according to the relative abundance of minute dusty inclusions. Some aggregates of the inclusions appear to be pseudomorphous after a mineral of micaceous habit, presumably kaolinite. Under polarized light, the slide consists of a fine mosaic-like felt of cryptocrystalline flakes (alunite?); the individuals are too small to permit a detailed study of their properties. Small grains of detrital quartz are included in the matrix and in some places the minute alunite (?) flakes show a radial structure about some of the quartz grains and kaolinite relicts.

There are minor amounts of other minerals present including notably fresh grains of microcline and sodic plagioclase, iron ore, epidote and zircon.

Sample No. 46.—This is a section cut from the core of borehole C15 at 37 feet, four feet above hard bedrock. A chemical analysis of the core from which it was taken is listed in Table 2. The hand specimen is recognized as

decomposed *gneissic granite bedrock* by a faint directional structure due to banded and elongated quartz grains.

This section presents similar features as *Sample No. 9*, but included in the cryptocrystalline groundmass are large flakes of the mineral kaolinite in various stages of alteration, and abundant quartz fragments. The latter occur in bands as elongated aggregates with a parallel orientation. Small quantities of iron ore and limonite stains are also present. The kaolinite occurs as colorless aggregates of distorted tabular flakes of fairly large dimensions, with a tendency towards a radial growth, and a wavy extinction. Some flakes have broken down to a cryptocrystalline aggregate similar to the base of the clay, but the outlines of former kaolinite crystals are still prominent in ordinary light as a mass of dusty-like inclusions.

CHEMICAL COMPOSITION.

A large number of alunite samples from the Pidinga Lakes, and other lagoons marginal to the Nullarbor Plain, have been chemically analyzed (Tables 2, 3) and the radicles present checked by spectrographic analysis.[2] The main ingredients of the alunite clays are alumina, sulphur trioxide, combined water, silica, potash and subordinate soda.

It was not possible by petrographic methods to be sure of the identity of the mineral forming the bulk of the clay, but a combination of microscopic work and chemical data confirms that it is kalio-alunite. Alunite is only sparingly soluble in water (5) but the potash contained in it is readily made available as soluble potassium sulphate by roasting, and a simple qualitative test based on this reaction (7) showed an abundance of alunite in the Pidinga samples.

Quartz grit was recognized under the microscope as an important constituent of both the high-grade and low-grade samples, and kaolinite was observed only in the low-grade material. If it is assumed that the silica of the high grade alunitic clay (Nos. 1, 2, 3, Table 3) is entirely quartz, a calculation of the relative percentage composition of the remaining potash, alumina, combined water and sulphur trioxide shows a ratio approximately equivalent to that required for the composition of alunite ($K_2O \cdot 3Al_2O_3 \cdot 4SO_3 \cdot 6H_2O$). Results of this calculation are as follows:

	Theoretical composition of alunite, percent	Sample 1, percent	Sample 2, percent	Sample 3, percent	Sample 4, percent
Potash	11.4	10.7	10.8	10.7	6.2
Alumina	37.0	36.3	36.9	36.3	51.3
Sulphur trioxide	38.6	38.8	38.2	39.1	24.8
Combined water	13.0	14.2	14.1	13.9	17.7

The low-grade sample (No. 4, Table 3) gives quite a different result and this is apparently due to the allocation of portion of the alumina and com-

[2] Determinations by A. C. Oertel, C. S. I. R. O. Division of Soils, Waite Institute, South Australia.

bined water to kaolinite ($Al_2O_3 \cdot 2S_1O_2 \cdot 2H_2O$). Strong evidence in support of this conclusion is the fact that the alumina and combined water remaining, after allowance for that necessary for alunite based on the potash content, are in the ratio of 17.6, the correct figure required for the composition of kaolinite.

The approximate mineral compositions of these samples can therefore be determined on the basis of this assumption and are as follows:

	Sample 1, percent	Sample 2, percent	Sample 3, percent	Sample 4, percent
Alunite	82.5	83.6	86.1	30.0
Kaolinite	—	—	—	44.0
Quartz	6.2	9.4	5.2	14.5
Accessories	11.3	7.0	8.7	11.5

The impurities in the clays (accessories) are ochre, absorbed water and soluble salts held therein, gypsum, etc.; the excess silica is shown as quartz, although research work (2, 3) on similar material from the Chandler (W. A.) lacustrine deposits has raised the possibility that silica also forms part of the alunite lattice as an isomorphous replacement of alumina. There is no evidence of such a condition in the Pidinga clays.

It is interesting to note that chemical analyses of kaolin clays and high-grade alunitic clays from the same horizons at Pidinga and Lake Tallacootra (Table 3) show that alumina, combined water and the minor constituents are present in consistently similar amounts in all samples. The only real difference is that the ratio $K_2O + SO_3 : SiO_2$ is high in the alunites and very low in the kaolin clays. In the light of the above calculations, this can be interpreted to mean that the only significant variable in the mineral composition of the clays as a whole is the ratio of alunite:kaolinite, and that there is a gradation in composition from clays rich in alunite to clays rich in kaolinite. This feature is illustrated diagrammatically in Figure 4.

X-RAY DIFFRACTION AND ELECTRON MICROSCOPE EXAMINATION.

X-ray powder spectrographs of representative samples from the Pidinga deposit were taken using FeK α radiation. The patterns confirmed that alunite and/or kaolinite are the main constituents of the clays, with quartz and feldspar in minor amounts, and it is concluded from these results that the cryptocrystalline alteration product of kaolinite observed in thin section is in all probability alunite.

Sample No. 5 (high grade alunite).—Consists mainly of alunite, with traces of quartz, feldspar and kaolinite.

Sample No. 4 (low grade alunite).—Minerals present in order of abundance are kaolinite, alunite and quartz.

Sample No. 6 (kaolin clay).—Consists mainly of kaolinite, with traces of quartz, alunite and feldspar.

Each of the samples consists entirely of crystalline material.

The preparation of an electron micrograph (Fig. 5) of high grade alunite (Sample No. 5) from the Pidinga deposit was kindly performed by Dr. S. G. Tomlin, of the Physics Department, University of Adelaide. Quartz grit and trace amounts of water-soluble salts known to be present in the clays are not represented in the micrograph.

The clay is seen to consist mainly of perfect hexagonal crystals ranging in diameter from 0.05 to 0.9 micron which are identified as alunite, and a small amount of kaolinite. The micrographs bear a striking resemblance to those of

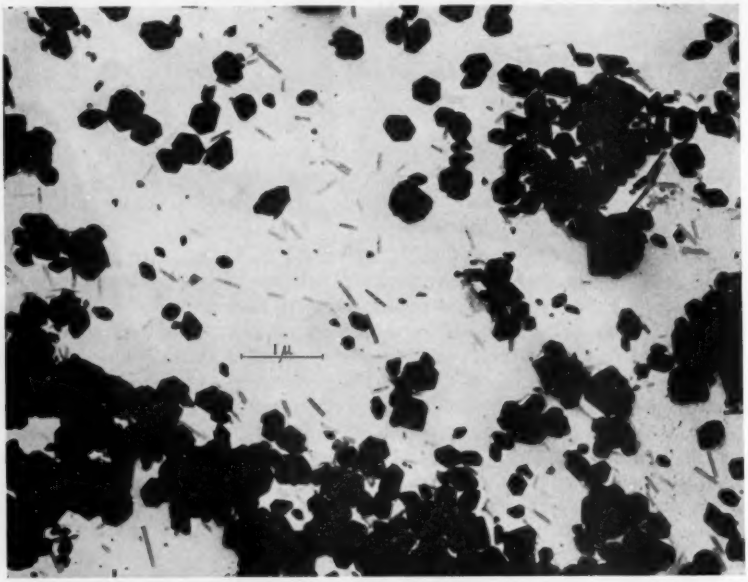

FIG. 5. Electron micrograph of high grade alunite from Pidinga. × 8,500.

samples from Chandler, Western Australia (2), except that diatom skeletons are present in the latter.

Chemical analyses of samples described in this section appear in Table 3.

ORIGIN.

Alunite is almost universally of secondary occurrence, and most theories put forward to explain its origin have ascribed the mineral to metasomatic replacement of potash feldspar or kaolin components of pre-existing rock. The presence of potash within the host rock has always been assumed, and inves-

tigators have confined their attention to the source and method of introduction of the sulphate radicle. In most deposits, the sulphuric acid responsible for the conversion of potash-bearing alumino-silicates to the sulphate is attributed to volcanic agencies. In other examples, the acid is explained as an oxidation product of pyrite or other sulphides. Physical and chemical conditions necessary for the alteration are not fully understood.

The geological history of the Pidinga alunite deposit is known in some detail. Prior to the Tertiary, Precambrian granite and gneiss were subjected to the normal processes of weathering. Clay detritus and soluble products resulting from decay accumulated in shallow depressions in the Precambrian rocks, portions of which are now occupied by the Pidinga lakes. In Lower Pliocene time the area was temporarily covered by a shallow sea, and following its recession, chemical redistribution of mineral matter in the ground water led to the development of a lateritic profile. The clays forming the lower pallid zone became alunitized, and were exposed in Pleistocene time due to the excavation of lagoons in these sediments by surface run-off from adjacent granite ridges.

Kaolinite-Alunite Association.—The Pidinga clays are known to have been derived by the weathering of feldspathic rocks, and the zonal distribution of alunite in them (Fig. 2) indicates that the actual alunitization involved secondary processes that were subsequent to the accumulation of the clay in the beds of the lagoons. Chemical analyses have shown that there is a gradation in composition from clays consisting entirely of kaolinite to pure alunite clays, and combined petrographic and X-ray examinations have contributed further evidence to suggest that the alunite was formed by metasomatic alteration of the kaolin clay.

The kaolinite-alunite association is common to many deposits (17), and other investigators have found evidence to suggest that kaolinite is an intermediate stage in the derivation of alunite from feldspar. In the White Horse alunite deposit, Utah (23), for example, the presence of small euhedral crystals of alunite in kaolinized feldspar phenocrysts shows that the kaolin developed first.

Retention of Potash.—Kaolin clay has been found to characterize the weathering products of granitic rocks throughout Australia, irrespective of the conditions under which they were formed (15), and an important result of its formation from feldspars contained in the granites is the "release" of potash, which in the usual case, however, is retained in the clay alteration products by adsorption (4).

Adsorption and base exchange readily take place in clays because individual particles, each containing unsaturated ions, are of such small dimensions that the clay is nearly all active surfaces (19). The special tendency for potash to be adsorbed in this way is well known (20), particularly from the results of soil investigations. Chemical analyses of fresh and kaolinized igneous rock (latite) shown below are extracted from the thesis of Willard and Proctor (23), as an example demonstrating the retention of alkalies by adsorption.

	SiO_2	Al_2O_3	Na_2O	K_2O
Fresh latite	60.47	19.29	3.24	5.11
Kaolinized latite	64.72	17.59	3.43	5.89

Another important factor influencing the retention of potash in the present example is that underground drainage is negligible and the ground water collects in a natural depression in Precambrian bedrock, where there is also a concentration of both the soluble salts and clay products set free by rock decomposition.

Source of the Sulphate Radicle.—The sulphate radicle is the only constituent of the alunite not contained in the clays, and for which it is necessary to find an extraneous source. This provides no problem as the clay bed overlies and is interbedded with lignite, which carries abundant pyrite and free sulphur, and pyrite is also a minor constituent of the Precambrian rocks in the

TABLE 4.

SELECTED GROUND WATER ANALYSES OF SAMPLES FROM THE FAR WESTERN PORTION OF SOUTH AUSTRALIA.

(Illustrating content of soluble aluminium sulphate in the presence of excess sulphuric acid.)

	Hundred of Bagster, Sect. 4N	Hundred of Catt, Sect. 4N	Hundred of Catt, Watraba tank reserve	Hundred of Horn, Sect. 12M	Hundred of Horn, Sect. 12M	Hundred of Catt, Sect. 12	Pidinga alunite deposit
Ions and radicles, grains per gallon							
Chlorine, Cl	380.10	263.90	786.85	1683.20	1185.30	1078.00	6737.50
Sulphuric acid, SO_4	78.72	115.63	122.63	243.12	193.52	159.30	1041.40
Carbonic acid, CO_3	nil	nil	nil	nil	nil	nil	nil
Nitric acid, NO_3	present	present	present	nil	nil	nil	nil
Sodium, Na	226.92	174.08	459.75	963.90	684.90	616.00	3871.00
Potassium, K							
Calcium, Ca	10.15	19.44	22.80	45.96	18.65	9.25	63.60
Magnesium, Mg	21.58	14.59	43.20	90.37	76.56	52.64	465.80
Alumina, Al_2O_3	1.91	1.01	0.58	8.04	4.07	19.26	16.98
Silica, SiO_2							
Iron, Fe							
Total	719.38	588.65	1435.81	3034.59	2163.00	1934.49	12196.28

district. The local ground waters could therefore be expected to be highly charged with sulphuric acid and ferric sulphate derived from the oxidation of sulphides. Conclusive evidence of its presence in post Middle Miocene times is the occurrence of a crystalline gypsum precipitate immediately below the marine limestone cap rock.

On the other hand, an abnormally high sulphate-chloride content is a present day characteristic of the ground waters in this far western portion of South Australia (Table 4), and similar conditions have no doubt existed for a considerable period. In view of this and the widespread occurrence of

alunite in association with laterites, and the absence of any notable quantities of sulphide minerals in proximity to the otherwise similar deposits at Lake Campion, it is thought that the regional effect was more important than the local development of sulphuric acid from pyrite. Another feature of the ground waters in the region is that they contain considerable quantities of soluble aluminium sulphate (Table 4). This is of particular interest as laboratory experiments (18) have shown that aluminium sulphate is a principal requirement for the production of synthetic alunite from feldspars.

Relation to Lateritization.—The localization of alunite beneath lateritic cappings reveals that the alunitization proceeded through the agency of chemi-

FIG. 6. Alunitic clay bed beneath ironstone and gypsum capping, Chundie Swamps.

cal eluviation during lateritization and the probable reason for this association is the unusual geochemical conditions existing in the lagoons. Whereas the lateritization of clays normally results in their complete leaching to bauxite, it seems that in the present example where there were conditions of partial saturation in basins of impeded drainage, alunite formed as an alternative product.

The physical change involved was chiefly one of drainage, from sluggish circulation under conditions of a permanent water table to vertical fluctuation of ground water accompanying lateritization (13). The change in chemical equilibrium was largely one of pH, effected by an increasing content or distribution of sulphuric acid in the ground water. The potash content of the clay was liberated by thorough leaching, and transported in acidic solution, to be

deposited in other localized horizons where the pH was influenced by the presence of alkaline reagents such as limestone.

The alunitization of the kaolinite probably followed along similar lines as those postulated by Frederickson (12) for the lateritization of certain clays to bauxite, but in the presence of potash, alunite would naturally take the place of the hydrated aluminium sulphate formed at an intermediate stage, and may remain stable as such. Du Bois (10) has previously described analogous processes for the genesis of bauxite and alunite.

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May 18, 1953.

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MOLYBDENUM BEARING GRANITE AND GRANODIORITE, RAUTIO, FINLAND.

VLADI MARMO AND LAURI HYVARINEN.

ABSTRACT.

In the southern part of the Parish of Rautio are granite and granodiorite that commonly contain small amounts of molybdenite and chalcopyrite. In this paper the authors discuss the petrography of these rocks and the connexions between the stages of metamorphism, the different mineral associations and the mineralization.

CONTENTS.

	PAGE
Introduction	704
Feldspars	704
Hornblende—Biotite—Chlorite	706
Ore Minerals	707
Chemistry of the Rocks	709
Metamorphism at Rautio	709
Conclusions	713
Bibliography	713

INTRODUCTION.

In Middle Finland, in the southern part of the Parish of Rautio, there is a large area of granite and granodiorite; the latter rock is commonly extensively granitized. This region attracted geologists because of its molybdenum and copper contents. A part of this granite-granodiorite area (4×4 km) has been studied in detail, and at several places the rocks have been tested by diamond drilling. During these investigations it was realized that the granite may contain up to 0.3 percent Cu and up to 0.01 percent Mo. If higher concentrations are present, they are so far unknown since the investigations are still in progress. The main mode of occurrence of the sulphides of copper and molybdenum, however, is already sufficiently well known to allow some metamorphic and mineralization questions to be discussed. The results given in this paper largely depend upon examination of diamond drill cores, as the outcrops within the region are scarce.

FELDSPARS.

In most specimens of the granite or granodiorite of Rautio the rock consists of a comparatively fine-grained "groundmass" of quartz, plagioclase and potash feldspar, with scattered insets of plagioclase and quartz, of plagioclase and microcline, and rarely of microcline alone, which is especially abundant in the vicinity of crushed zones. In one loose boulder containing more than 1 percent Mo, there were very large insets of microcline only.

The plagioclase porphyroblasts are large, commonly saussuritized, and in extreme cases epidote is so abundant that it fills most of the middle part of the crystal. The homogeneous plagioclase porphyroblasts generally contain an average of 33 percent An (Table I). However, a distinct zoning may occur in the plagioclase, and then the marginal part of the zoned crystal consists of oligoclase with 12 to 15 percent An and the central part 25 to 26 percent An. The zones are commonly separated from the middle part of the crystal by a narrow strip consisting of minute grains of epidote and of scales of sericite. As seen from the Table I, if zoned plagioclase occurs, the plagioclase of the groundmass is generally of the same composition as the marginal part of the zoned plagioclase crystals.

The saussuritized grains of plagioclase commonly contain calcite as well as epidote, and the plagioclase is in such cases albitic.

In addition to the zoned or zone-free feldspars, there are instances of occurrence of both feldspars within the same grain in which potash feldspar is

TABLE I.

AN-CONTENT OF PLAGIOCLASE IN THE GRANITIC ROCK OF RAUTIO, DETERMINED BY MRS. TOINI MIKKOLA OF THE GEOLOGICAL SURVEY OF FINLAND, ON THE U-STAGE.
All samples are from diamond drill core 1.

	"Depth"	% An in the middle of the plagioclase	% An in the marginal zone	% An in the plagioclase of the "groundmass"
1.	44.00 m	25	12 to 14	~15
2.	56.50 m	33	33	24
3.	98.40 m	26	23	21 to 23

1. Granite containing no hornblende; the biotite is quite unaltered. The plagioclase is distinctly zoned.

2. Granite containing epidote in abundance; no zoning of plagioclase has been observed, and no saussuritization of the examined grains of plagioclase.

3. Gray granodiorite containing unaltered biotite, often with a core of hornblende. The porphyric grains consist of indistinctly zoned plagioclase only.

surrounded by plagioclase that has evidently grown later, and in part also replaced the potash feldspar. Such replacement is especially well developed in some parts of diamond drill core 1 (Fig. 1), where there are strongly saussuritized grains of plagioclase that still contain remainders of potash feldspar.

But there are also cases of feldspar containing potash feldspar younger than the plagioclase.

Myrmekite is not very common at Rautio, but where it does occur, it is always connected with definite parts of the rock. As seen in Figure 1 the myrmekite occurs in drill core 1 between 24 and 35 m, where the molybdenum content is highest. Also in diamond drill core 5 myrmekite and molybdenum characterize the same part of the drill core. Potash feldspar is also most abundant in the more disturbed parts of the rock.

Both feldspars are commonly enveloped by a "zone" that is colored red by hematite pigment. Also the color of the red feldspar (less common than

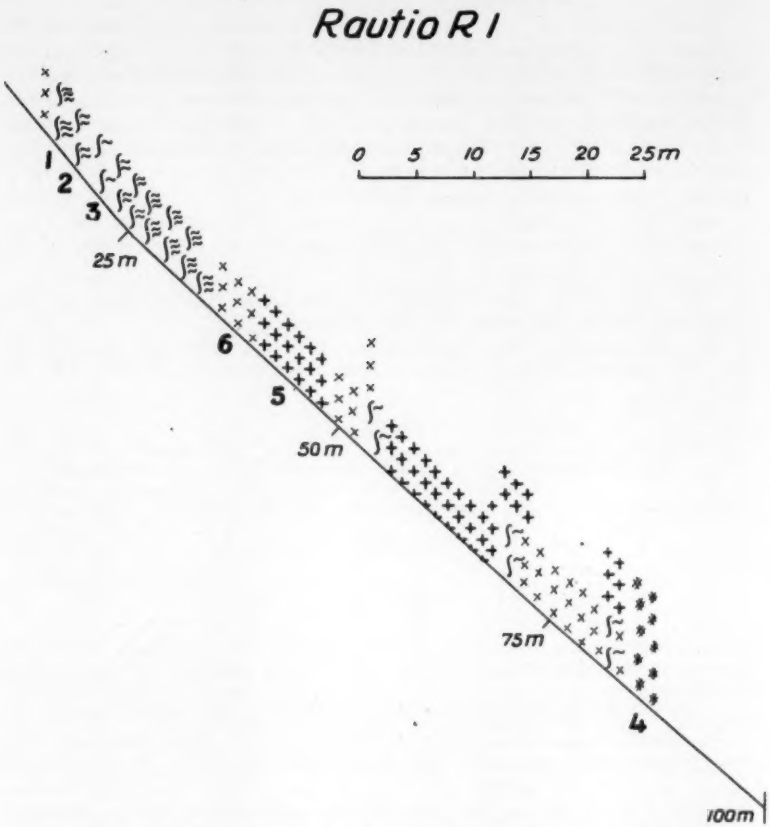

FIG. 1. Drill core 1, Rautio: 1, myrmekite dominant; 2, myrmekite common; 3, myrmekite occasional; 4, potash feldspar commonly replaced by plagioclase; 5, epidote abundant; 6, epidote moderate.

gray feldspar) may depend upon similar hematite pigment. In diamond drill core 1 (Fig. 1) the hematite-bearing rims occur between 55 and 65 m, and on both ends of that part of the core the reddish feldspar is common. Within the same part of the drill core there are narrow quartz veins, likewise red due to hematite pigment.

HORNBLENDE—BIOTITE—CHLORITE.

Microscopic study of the Rautio granite and granodiorite indicates that all of the rocks contained primarily hornblende, which has been largely altered

to green biotite, and in part to chlorite. Brown biotite, on the contrary, seems to be of primary origin, and it commonly contains minute grains of zircon, absent in the green biotite.

The biotite is commonly altered to chlorite, and in the chloritized parts hornblende is absent. However, if hornblende is present, then the chloritization is very weak. Figure 2 shows a short section of drill core 1 (between 28 and 55 m) in which the rock containing brown biotite and slightly altered hornblende merges into green biotite rock with residuals of hornblende surrounded by biotite. Where the hornblende disappears, the biotite is distinctly and evenly chloritized. The stages of metamorphism are then reversed, grading into a rock containing unaltered hornblende and non-chloritized biotite.

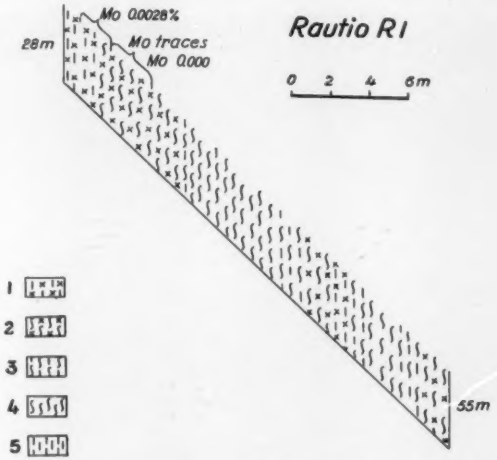

FIG. 2. Drill core 1, Rautio: 1, hornblende granodiorite; 2, hornblende granodiorite with some biotitized hornblende; 3, granodiorite with completely biotitized hornblende, and biotite slightly chloritized; 4, biotite granite with completely chloritized biotite; 5, biotite granite.

The parts of rock containing determinable amounts of molybdenum are those with residuals of hornblende and weak chloritization of the biotite.

ORE MINERALS.

Since diamond drilling has not as yet established any economic ore, the rich ore-bearing boulders from the investigated area gave better opportunity for the study of the ore minerals. The parent rock of the ore in the boulders is similar to the rock of the outcrops—granite and granodiorite. The ore minerals are molybdenite, chalcopyrite, pyrrhotite, and pyrite, with minor sphalerite, valleriite and covellite. They occur in quartz veins, but also as thin impregnations. The molybdenite generally occurs alone, but in some

places along with chalcopyrite and iron sulphides. In one outcrop the molybdenite occurs as a thin dissemination, but chalcopyrite occurs in veins containing quartz or chlorite. Impregnation of chalcopyrite rarely occurs in the granite, along with pyrrhotite, pyrite or a little sphalerite.

The molybdenite and chalcopyrite apparently belong to separate stages of mineralization but overlap in some instances. Molybdenite commonly contains small blebs of chalcopyrite, which at first glance resemble the products of exsolution, but no unmixing appears to have occurred. Rather, these particles have evidently been introduced along the planes of the lamellae of molybdenite, and are genetically contemporaneous and similar to the narrow veinlets of chalcopyrite that cut the grains of molybdenite. In all sections

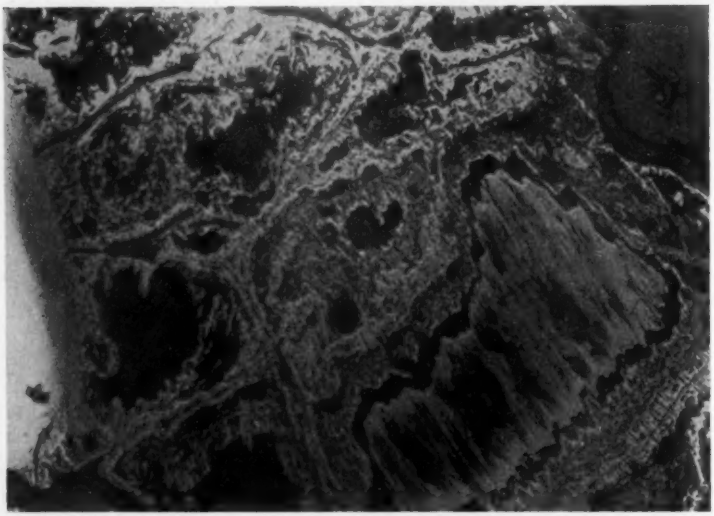

FIG. 3. Covellite replacing pyrrhotite lamellaewise; chalcopyrite in upper right and at left; the fine-grained network consists of marcasite-like sulphide, marcasite, pyrite, and limonite. Rautio. Polished section. × 150. Photo V. Marmo.

examined, from boulders, outcrops, and diamond drill cores, the chalcopyrite is of distinctly later origin than the molybdenite.

The association of molybdenite and chalcopyrite permits the determination of the lowermost temperature of molybdenite formation, since cubanite lamellae occur in the chalcopyrite. (In most cases, however, no cubanite has been observed.) According to Schwartz (12), the cubanite forms a solid solution with chalcopyrite at 450° C. Merwin and Lombard (7) reported that even at 400° C the cubanite lamellae disappear from the chalcopyrite. Hence it seems that the chalcopyrite containing lamellae of cubanite was

deposited between 400° and 450° C. Because, in all cases examined at Rautio, the chalcopyrite is younger than molybdenite, this temperature may be considered as the lowest possible for the deposition of the molybdenite.

The deposition of chalcopyrite evidently continued to a lower temperature for, where cubanite is absent, some valleriite may occur with chalcopyrite. It forms narrow veins, which due to the strong pleochroism and anisotropy of the valleriite are easily definable. If alone, the valleriite is still stable at 410° C, (4, p. 87), but where it occurs with chalcopyrite, the pyrrhotite and chalcopyrite were formed at 225° C. Since the valleriite occurs at Rautio with chalcopyrite, this association may indicate that the valleriite has been deposited at a lower temperature than that of the decomposition of valleriite, that is below 225° C.

Covellite envelopes grains of chalcopyrite or forms replacement veinlets in sphalerite (9, p. 474). Covellite also replaces pyrrhotite lamellaewise (Fig. 3); this is associated with a thin network of fine-grained pyrite, marcasite, and a marcasite-like supergene sulphide (6, 1953).

Covellite has commonly been interpreted as evidence of late mineralization, and as a supergene sulphide enrichment. The Rautio covellite is considered to be supergene.

CHEMISTRY OF THE ROCKS.

The discussion of the chemistry of the rocks of Rautio is based on only two complete chemical analyses (Table II). Anal. 1495 is of granite containing 0.003% Mo; anal. 1496 is mega- and microscopically quite similar to 1495, but contains no Mo (0.0000% Mo). Both analyses are otherwise rather similar to each other, except for their alkali content. The potassium in the molybdenum-bearing granite is distinctly higher (when compared with the content of sodium) than in the other granite. Further, the molybdenum-bearing granite is richer in SiO_2, and in addition it contains more iron. The microscope, however, discloses no addition of potassium feldspar in the molybdenum-bearing rock, but evidently the excess of potassium has been used together with excess FeO and pre-existing SiO_2 to form biotite. The excess of aluminum, obtained by calculation of the normative minerals of the analyses, can be explained in the same manner. In spite of the addition of SiO_2 the rock used for anal. 1495 contains, as revealed by the microscope, less quartz than that used for anal. 1496, because the SiO_2 was used for the biotite. The "biotitization" seems to be connected to the granitization, the "desilicification" being its first stage, as remarked by Reynolds (10). Hence, the deposition of molybdenite seems to have occurred in connection with the granitization of the rocks.

METAMORPHISM AT RAUTIO.

It seems that the deposition of molybdenum occurred under conditions by which hornblende was changed to biotite. This phenomenon corresponds to the conditions of amphibolite facies, and since only a little hornblende occurs in the granite of Rautio, the main metamorphism must have occurred under the same conditions.

The occurrence of myrmekite and of potash feldspar in plagioclase is of interest. As seen from Figure 1, myrmekite occurs in diamond drill core 1 only within a short section part, which part contains molybdenum (average 0.003%). Further, according to the chemical analyses, this part has a higher ratio K_2O:Na_2O (= 1.032) than the rock containing no molybdenum (ratio = 0.924). Also in drill core 5, the part containing myrmekite (65–80 m; 98 to 102 m) is molybdenum-bearing (0.008 and 0.004% respectively). Between 13 and 20 m of diamond drill core 3 myrmekite likewise occurs, but there the molybdenum content has not been determined. In all cases mentioned the biotite is quite fresh or shows only slight signs of chloritization.

As is seen from Figure 4, the epidotization of the plagioclase is inconsiderable or slight in the parts of granite containing myrmekite; on the other hand, in strongly epidotized parts myrmekite has never been observed. This

TABLE II.

ANALYSES OF GRANITE OF RAUTIO.

Analyst P. Ojanperä at Geological Survey of Finland.
Anal. 1495: Granite from the diamond drill core 1, between 22.50 and 24.20 m.
Anal. 1496: Granite from the same diamond drill core between 43.60 and 46.15 m.

Constituent	1495	1496	Normative minerals		
SiO_2	72.58%	72.03%	Apatite	0.84	1.01
TiO_2	0.26	0.29	Sphene	0.69	0.78
Al_2O_3	13.73	13.87	Ortoclase	24.46	22.24
Fe_2O_3	0.80	0.94	Albite	34.06	34.59
FeO	1.44	1.40	Anorthite	4.93	4.45
MnO	0.08	0.04	Corundum	0.75	1.43
MgO	0.75	0.88	Magnetite	1.16	1.39
CaO	1.63	1.68	Enstatite	1.9	2.2
Na_2O	4.00	4.12	Ferrosilite	1.51	1.19
K_2O	4.13	3.82	Quartz	29.41	30.06
P_2O_5	0.34	0.39		99.71	99.32
CO_2	trace	trace			
H_2O+	0.56	0.51	$\frac{An+Alb}{Or}$	= 1.509	1.755
H_2O-	0.04	0.06			
	100.04	100.03	% Or in total feldspar	38.55	32.70
Mo	0.003	0.0000			
K_2O/Na_2O	1.032	0.924			

observation contradicts the statements of Väyrynen, who wrote regarding the granodiorite from Ostrobothnia (15, p. 14): " . . . sondern es ist eine Reaktionszone, die also mit der Bildung des Epidots, Muskovits und Chlorits zusamenhängt, welche Minerale nur in Verbindung mit dem Myrmekit auftreten." Edelman (3) likewise assumed that the origin of myrmekite corresponds to a somewhat low temperature; this opinion was not adopted by Seitsaari (14, p. 95) who wrote: "As regards the temperature during myrmekitization, the author, contrary to Edelman holds that it has not in general been very low. In the rocks containing considerable amounts of chlorite, muscovite, epidote, etc., myrmekite is sparse and weak in comparison with that in the products of 'normal' granitization, although abundant potash has been introduced." The present authors agree with the opinion of Seitsaari, and from their conclusions concerning the temperature of deposition of

molybdenite, the myrmekitization of Rautio may be considered as a phenomenon governed by the conditions corresponding to the amphibolite facies.

In discussing myrmekite, Sederholm wrote (13, p. 142): "The great interest of all the synantetic minerals lies in the fact that they seem to be chemical formulas written in stone. Often their interpretation seems to lie so close at hand, that it appears only necessary to grasp a pen and write them down on paper." He remarks, however, that this "writing" may be difficult since there may be materials introduced from afar, and other materials re-

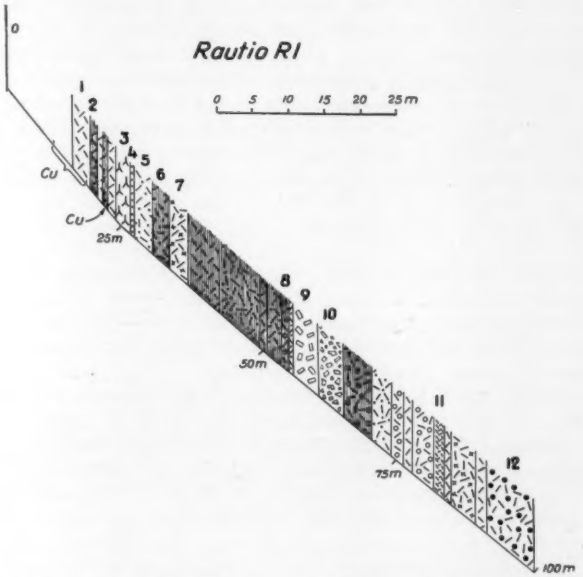

FIG. 4. Drill core 1, Rautio: 1, gray porphyrite granodiorite; 2, pink porphyritic granodiorite; 3, granite; 4, aplite; 5, gray porphyritic granodiorite containing phenocrysts of plagioclase and potash feldspar; 6, pink porphyritic granodiorite containing phenocrysts of plagioclase and potash feldspar; 7, porphyritic hornblende granodiorite; 8, porphyritic granodiorite containing abundant epidote; 9, gray porphyritic granodiorite containing zoned phenocrysts of plagioclase; 10, gray porphyritic granodiorite containing phenocrysts of plagioclase and quartz; 11, felsic granodiorite; 12, porphyritic granite containing phenocrysts of plagioclase only.

moved. In the case of Rautio, the movement of different materials can be traced without difficulty because the reactions have taken place within a comparatively small area.

Different investigators have assumed two possibilities concerning the origin of myrmekite: according to some of them (1, 13) the myrmekite should result from the replacement of potash feldspar by the plagioclase; others as-

sume that myrmekite originates due to replacement of plagioclase by potash feldspar (2).

If the first alternative is accepted, then the potassium would be removed and deposited in new minerals. This redeposition can occur in a form of biotitization of hornblende, as at Rautio, and the origin of the myrmekite there can be explained as being dependent on "albitization" of microcline; on the other hand, according to the chemical analyses, it seems that the rock containing myrmekite has obtained potassium from other sources.

If the myrmekitization is a result of addition of potassium, then the albite would be expected to have been replaced, and so the phenomenon, also observed by Edelman (3) and Seitsaari (14), that the plagioclase of myrmekite is richer in anorthite than that of phenocrysts, is easily understood. Consequently, in this case the sodium is removed; hence there must be minerals in which the sodium should be found anew. As seen from the figures of Table I, in the granite containing zonally developed phenocrysts of plagioclase, the outer part of them is more albitic than the inner part, and also the fine-grained plagioclase of the groundmass is as albitic as the margins of the plagioclase phenocrysts. Hence, it seems that the younger plagioclase has been more albitic than the older. Furthermore, it can be seen from Figure 1 that in drill core 1, between 84 and 87.5 m, occur phenocrysts containing patches of potash feldspar enclosed by plagioclase. Here replacement of microcline by plagioclase appears to have taken place. Hence, can it be, that in the case of Rautio, both potassium- and sodium-metasomatism took place? If so, the potassium introduction caused the replacement of albite by potassium feldspar with contemporaneous formation of myrmekite; during these reactions the sodium released would replace potassium feldspar elsewhere in the rock. This could give first potassium metasomatism, and then owing to released sodium, "albitization" of potassium feldspar. That such reactions under the same conditions are possible has been detected by O'Neill (8) who has examined experimentally the hydrothermal alteration of feldspars. According to his experiments, under quite similar conditions and depending only on the amounts of K and Na ions in the hydrothermal solutions, the albite may be replaced by potassium feldspar, or the last-mentioned by the albite. This replacement can occur both in acid, neutral, and basic solutions, at a temperature of 400° C. According to Gruner (5) the presence of aluminum inhibits this base exchange, at least in neutral solutions.

The saussuritization of plagioclase does not commonly occur at Rautio in connexion with myrmekite; elsewhere, however, it has often been observed, and the conditions corresponding to the saussurite facies have governed the stage of metamorphism at Rautio within large areas.

The red hematite margins of the feldspar previously mentioned, occur especially in connexion with the most strongly epidotized parts of the rock, and hence it can be assumed that both the origin of hematite rings and of the epidote occurred under similar (or the same) conditions. The red color of feldspar has often been attributed to the presence of a very thin hematite impregnation. In the case of Rautio the red colored feldspar mainly occurs in connexion with the rock rich in epidote, hence in the parts characterized

by the range of metamorphism corresponding to the saussurite facies. It seems to the present authors that the hematite pigment is a result of hydrothermal activity under the conditions of the same facies.

The assumption that the hematite pigment originated due to exsolution from the feldspar does not seem to be probable since Rosenqvist (11) has shown that the ferri-feldspar is very rare, and that the origin of hematite pigment due to exsolution must be considered as a very exceptional case. At least a part of the hematite at Rautio may have originated from biotite during its chloritization, the released iron being oxidized and deposited as hematite in the form of a fine-dispersed pigment.

In addition to the occurrence of the ore minerals previously discussed, it may be mentioned that in drill core 6, the chalcopyrite occurs in conjunction with cataclastic quartz veins, and there cubanite lamellae have been observed. Furthermore, one outcrop discloses similar narrow quartz veins cut by potassium feldspar, younger than the quartz veins. The main part of chalcopyrite, however, occurs in conjunction with epidote and chlorite, and has evidently been deposited under conditions corresponding to the saussurite facies.

CONCLUSIONS.

From the foregoing description and discussion the following conclusions may be drawn:

1) The myrmekite has originated under conditions corresponding to the amphibolite facies, and evidently in close relation to the biotitization of hornblende.

2) The myrmekitization occurs as a result of potassium metasomatic alteration of albite; the released sodium has then taken part in the "albitization" of potassium feldspar at other places in the same rock body.

3) The deposition of the molybdenite has occurred under conditions somewhat similar to those obtaining for the phenomena mentioned in (1) and (2), and at a somewhat lower temperature the chalcopyrite containing cubanite lamellae was deposited.

4) The main part of chalcopyrite was deposited at a still lower temperature, which probably corresponds to the conditions of the saussurite facies, and under the same conditions the epidotization of anorthite and the chloritization of biotite took place.

ACKNOWLEDGMENTS.

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HELSINKI, FINLAND,
June 12, 1953.

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TRACING OF GLACIAL BOULDERS AS AN AID TO ORE PROSPECTING IN SWEDEN.

ERLAND GRIP.

ABSTRACT.

During prospecting in Fennoscandia glacial ore boulders in the moraine have given indications of great value, and systematic search for such boulders is regularly made. Several examples of boulder trains in Sweden are mentioned and how they led to discoveries of new ore deposits.

INTRODUCTION.

THE Quaternary glaciation has left its traces all over Fennoscandia. Glacial moraine is the most common soil, and glacial ore boulders have proven to be excellent indicators of ore. As long as 200 years ago the Swedish scientist Daniel Tilas showed that discoveries of erratic ore boulders could be used for locating ore bodies, and he also indicated the main direction of movement, although the cause of the transportation of the boulders was not known at that time.

When the course of the Quaternary glaciation became known observations were made from which the ice movement in different parts of Fennoscandia could be determined. For this purpose glacial striae and boulders played a great part. Systematic search for ore boulders leading to the discovery of a deposit, however, was made only in the beginning of the 20th century. A classical example is the discovery of the Outokumpu copper deposit in Finland. The Geological Commission had inquired after a meteorite, which was supposed to have fallen in East Finland. During excavations at Kivisalmi canal, a heavy, rusty boulder of about five cubic meters had been found at a depth of 3 meters, and taking it for the meteorite the foreman sent a sample to the Geological Commission. However, the sample proved not to be of meteoric origin but of a sulphide ore rich in copper. Investigations were started immediately to find the motherlode of the boulder. In 1910, O. Trüstedt succeeded in localizing the large copper deposit of Outokumpu after two years' work of tracing a boulder train from the first find some 50 kilometers towards the NNW. M. Sauramo (4)[1] has supplied a detailed description of this, as well as of some other Finnish boulder trains.

In the northernmost part of Sweden, I. Högbom by systematic studies of boulders in the moraine succeeded in finding a graphite deposit at Äijarova in 1916. In the following year P. Geijer (2) presented the results of his studies of the ice movement and transportation of boulders from the large iron deposits in the same region. Just after World War I when prospecting started in the Skellefte district in Northern Sweden, boulder hunting became an im-

[1] Numbers in parentheses refer to Bibliography at end of paper.

portant part of the work. There the ground is covered to a great extent with a heavy overburden, and hardly one percent of the bedrock outcrops. The cover of moraine is thick, averaging 6 to 7 meters, and within large continuous areas of swamps there are no outcrops. Loose ore boulders in the moraine, however, supplied the first information of sulphide ore in the district, and during the continued prospecting ore boulders have always proved to be the most important indications of ore. Therefore, systematic hunting for such boulders has been carried out on a large scale. The local inhabitants often

FIG. 1. Position of the six boulder trains described in this paper. 1. Rakkejaur, 2. Näsliden, 3. Storbodsund, 4. Harmsarvet, 5. Laisvall, 6. Ultevis.

have been able to give the geologists important information, and those who proved to be particularly capable in finding ore boulders have been employed as boulder hunters. By mapping the discovered boulder trains and determining the direction of the ice flow by striae or other means, the position of the ores has been approximately located. Also geological mapping and tectonic analysis of the bedrock have rendered important indications for the location of the ore. Only in a few cases, however, have purely geological methods led to the discovery of an ore deposit, and in all other instances resort was to

geophysical methods. However, in the Caledonian mountains, and especially in the eastern border of this mountain range, geophysical methods have not proved to be very useful. There drilling or excavations must be carried out solely on geological indications, and particularly by the guidance of boulder trains.

The importance of ore boulders and boulder trains for prospecting in Sweden has been described previously by several authors, and especially J. Eklund (5), A. Högbom (2) and G. Lundqvist (3) have given instructive examples. Five of the boulder trains, which I describe below, have been discovered by the prospecting work of the Boliden Mining Co. in different parts of the country, and the sixth and most northern one has been mapped by the Geological Survey of Sweden. Taken separately these boulder trains are characteristic for these different parts of the country from which they originate. Generally, however, it is not possible to obtain such nice pictures of boulder trains, and we have to be content with considerably fewer and perhaps more scattered boulders. In the Skellefte district, which is rich in ores, the maps of boulders often become complicated because boulders from different deposits located along the direction of ice flow become jumbled together. It is then necessary to examine each boulder and try to distinguish different types of ore. In this manner it may be possible to distinguish boulders from different deposits.

EXAMPLES OF BOULDER TRAINS AND RESULTING ORE DISCOVERIES.

Rakkejaur.—While surveying in the Skellefte district in the summer of 1921 two geologists came to a small farm, where the farmer showed them a box with glittering stones found by him. Among mica schists and other stones of no value there was a piece of pyrite ore. The farmer did not remember exactly where he had found it but thought it was along a path, which he described. The geologists followed the path and found first one ore boulder and then several others with pyrite and sphalerite. Continued search from the original boulders to the NNW, against the direction of ice flow, led to the discovery of rusty outcrops which represented the outcropping of an important ore body, which was named Rakkejaur.

The Rakkejaur deposit, with an area of 19,000 square meters, is the largest ore body in the Skellefte district. Later the boulder train leading to the discovery was completely mapped. It is a nice example of a regular boulder train such as can be mapped where the moraine is insignificantly hidden by covering material.

The Rakkejaur body is a low-grade pyrite-sphalerite ore replacing quartzite and slate and containing some lenses of arsenopyrite and copper ore. Figure 2 shows the ore deposit, the boulder train and the direction of ice movement. The boulder train is very regular and has an insignificant lateral extension. The direction of the boulder train coincides with that of the younger glacial striae. The size of the boulders varies from a few kilograms to more than one ton. As a rule the shape of the boulders is angular in the vicinity of the ore and increasingly rounded with greater distance from the ore body. They

FIG. 2. Rakkejaur. The large boulder train from the sulphide deposit. F. Kautsky 1921 and later.

are very little weathered, despite the fact that some of the arsenopyrite boulders which have been broken with a hammer have weathered to scorodite in a few years.

Figure 2 shows only that part of the boulder train that has been mapped in detail. The boulder train can, however, be traced far away to the SSE

but the boulders are more scattered and swamps commonly conceal the surface of the moraine.

The trained boulder hunter often is able to find ore boulders that do not reach the surface. This is because vegetation near ore boulders is often poorer or may have a burned appearance due to diffusion of disintegration products of the ore. Many of the Rakkejaur boulders were found by the use of such knowledge.

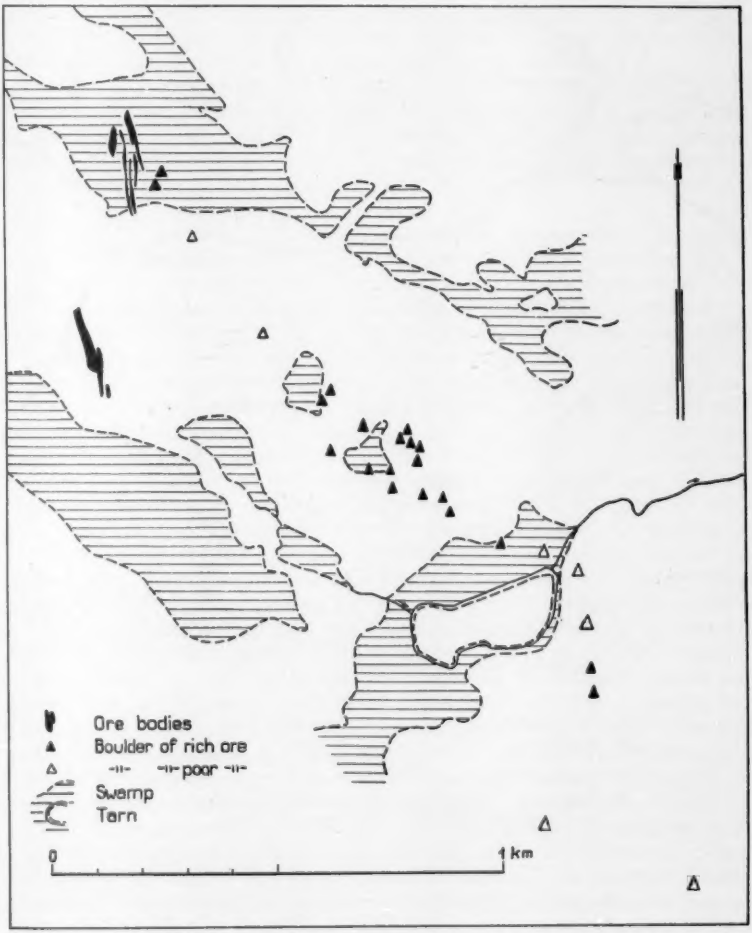

FIG. 3. Näsliden. Ore bodies and boulder train. F. Kautsky 1921, later completed.

Näsliden.—At Näsliden the first ore boulder was also found by local inhabitants and a geologist was informed of the discovery in the summer of 1921. Here the search for boulders was difficult because of heavy vegetation of moss, but after intense work a boulder train of some 20 boulders of zinc-bearing

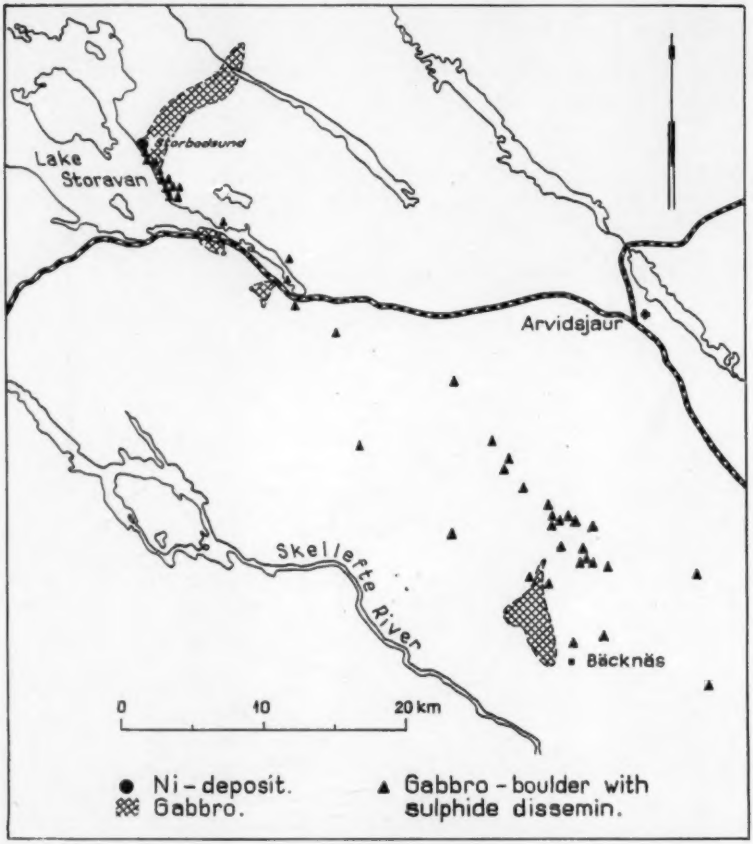

FIG. 4. Storbodsund. Nickel deposit and train of sulphide-disseminated gabbro boulders. W. Larsson 1942.

pyrite ore appeared. The area indicated by the boulder train was investigated by electrical prospecting (galvanic measurements), and diamond drilling in 1922 of the electrical indications disclosed ore under a cover of about 10 meters of moraine. In the neighborhood of the deposit many other anomalies were

found, some of which were drilled but proved to be caused by black slates with disseminations of graphite and pyrrhotite.

In 1947, however, the Näsliden ore body and its surroundings were again electrically surveyed, this time with the "Loop frame method" 3600 a/s. The new survey gave a much clearer picture of the indications than the older one, and it was completed with magnetic (Arvela balance) and gravimetric (Worden gravity meter) tests. A good electrical indication, 400 meters south of the old deposit, was confirmed both magnetically and gravimetrically, and drilling proved a zinc- and copper-bearing pyrite ore, which was considerably larger than the old northern deposit. This southern deposit was also covered by about 10 meters of glacial drift.

It is rather striking that not a single ore boulder referable to the southern ore body has been found although the boulder grounds to the leeward of this deposit are as good as to the leeward of the northern one. Boulder hunting has been carried on since the discovery of the new ore body but with negative results. The reason may be that the surfaces of the two ore bodies were of different shape when the ice sheet moved over the country. The southern ore body may have been protected against attack from the glacier by a flat surface, whereas the northern ore body may have had a rougher surface that permitted the ice to pluck and remove pieces of the ore.

This example shows that the ore bodies are not always indicated by boulders even if the soil to the leeward of the deposit consists of moraine.

Storbodsund.—At Bäcknäs, 25 km south of Arvidsjaur, there was found a large boulder of gabbro interspersed with sulphides, and containing some nickel and copper. Northwest of Bäcknäs there is an area of gabbro and the boulder could have been expected to originate from there. Outcrops, however, were sparse and detailed boulder hunting had to be carried out. Several new boulders of nickel-bearing gabbro were found over a broad front, but the boulders did not originate from the adjacent intrusive since they were followed over it and traced farther and farther to the northwest.

On the northern shore of Lake Storavan the number of the boulders as well as their size rapidly increased. Suddenly, however, the boulder train ended after it had been followed 55 km. Continued investigations around the end of the boulder train proved that here was an area with gabbro not hitherto known, forming the western border of a large granite massive. The motherlode of the long boulder train was now to be sought within the gabbro belt on the northern shore of Lake Storavan. The dissemination ore in the gabbro boulders was too low grade to be of any direct interest, but it was considered possible that more compact nickel-pyrrhotite ore might occur with the disseminated ore. Since such massive ore weathers very rapidly it would not be expected to be found in boulders.

The suspected area at the end of the boulder train was investigated with electrical and magnetic methods. The strongest of the indications was drilled and proved to be caused by compact nickel-pyrrhotite ore. It had the shape of a flat sheet lying between the gabbro and underlying older rhyolite and granite. Only a minor part of the small ore body outcropped at the surface of the bedrock, and was covered there with 5 meters of moraine.

Thus, a small ore body, of only some thousand tons, had been discovered after its boulder train had been followed 55 kilometers.

Harmsarvet.—Tracing of ore boulders has also been used with success in modern prospecting in the old mining district of Bergslagen in Middle Sweden. An instructive example of a boulder train which led to the discovery of an ore deposit in this part of the country is found at Harmsarvet, 14 km northwest of the town of Falun (Fig. 5).

The boulder hunting was carried out during the years 1935–1937. Over a distance of 1,300 meters from the first ore boulder, weighing more than one

FIG. 5. Harmsarvet. Silver deposit and its boulder train. E. Dahlström 1937.

ton, no boulders were found. Beyond this distance there were numerous boulders, but after another 300 meters the boulder train seemed to terminate. The ore in the boulders was composed of very rich silver ore with native silver, argentite, sphalerite and galena. The content of sulphides, however, was so low that electrical prospecting could not be expected to indicate the mother-lode and continued investigations of the thick moraine cover were necessary. Where the boulder train ended at the surface, the hunting proceeded by digging of trenches. Investigation of deeper sections of the moraine revealed ore boulders that did not reach the surface and these were followed another 700

meters, where the boulder train definitely ended. At this point a trench was dug to the bedrock through 6 meters of moraine. Sparse disseminated ore was found and the strike could be determined. Then diamond drilling was carried out and in the fourth hole rich silver ore of the same character as in the boulders was discovered.

The boulder train of Harmsarvet shows that the boulders may not reach the surface of the moraine for a long distance, and also how narrow the lateral dispersion of the boulders may be in this part of the country.

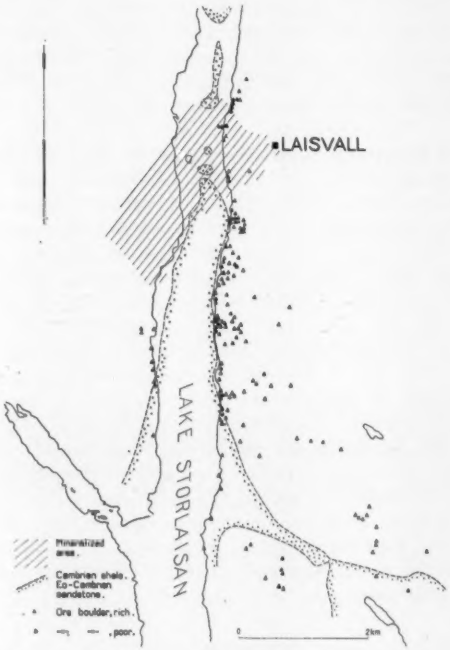

FIG. 6. Laisvall. Boulder train indicating the lead-mineralized area. F. Kautsky 1938.

Laisvall.—Along the eastern border of the Caledonian mountain range in Lapland, there is an autochthonous sandstone that can be followed through almost the whole of Lapland. About 1930 some galena had been found in sandstone boulders and outcrops, but no deposit of economic value had been discovered.

Because of these indications, however, more extensive prospecting was carried out in this part of the country in 1938. The most important discovery that summer was a large boulder train at Laisvall with boulders of sandstone

containing a high percentage of lead (Fig. 6). The first ore boulder was found towards the southeast and the boulder train was then followed about 7 km to the shores of Lake Storlaisan. The boulders had a maximum size of four cubic meters, and in some cases the content of lead was very high.

The stratigraphy of the area is briefly as follows: A peneplained Archaean granite is covered with weathering breccia, arkose, and mudstone. This is followed by about 40 meters of Eo-Cambrian sandstone in three different beds, of which the lower and the upper were found to contain disseminations of galena. The sandstone is overlain by a series of Cambrian shales, and the bituminous members of Middle Cambrian are generally cut off by overthrust nappes. The sediments dip only a few degrees to the northwest.

At the northern end of the boulder train the rocks of the nappe were found down to the level of Lake Storlaisan, and the motherlode of the ore boulders was estimated to be at the bottom of the deep lake, which fact was proved later by drilling.

On geological indications, systematic diamond drilling was started in January 1939 along the shores of Lake Storlaisan. Disseminations of galena were soon found in the sandstone, and in March lead ore was discovered by drillhole number 13. The investigation of the mineralized area then went on and a continuous ore deposit under and on both sides of the lake was discovered. The ore outcrops only in some windows of the covering shales and nappes at the bottom of the lake and it was the boulders from these parts that led to the discovery of the deposit. Exploitation was started in 1943 and at present the output of the Laisvall mine is about 300,000 tons of ore a year.

Ultevis.—In 1940 the Geological Survey of Sweden was informed of a boulder of manganese ore found by the local inhabitants at the Arctic Circle in the neighborhood of the railway station of Murjek, and with this indication prospecting for the motherlode of the boulder was started. During several summers boulder hunting and detailed geological investigations were carried on. A long boulder train with several and long interruptions was traced, and in 1943 the motherlode of the boulders was at last located. It was a manganese mineralized zone in the mountain of Ultevis, 125 km from the original find. In Sweden this is the longest distance a boulder train has been followed from the first boulder indication to the deposit.

CONCLUSIONS.

Hunting for ore boulders is an extraordinarily sensitive prospecting method. In a boulder train such as that of Rakkejaur where the frequence of ore boulders is exceptionally high, the content of ore boulders found amounts to not more than 50 grams per ton of moraine, and in most cases it is very much lower. A necessary condition for the application of the method is that the ore does not weather too easily. Fennoscandia, and especially its northern parts, offers very suitable conditions. The Quaternary continental ice sheet withdrew from the country less than 10,000 years ago, and afterwards in the cool climate chemical weathering has been insignificant. The sparse vegetation in the pine-forests generally does not hide the boulders at the surface, and this is a favorable factor not to be underrated.

In some parts of Fennoscandia it is difficult to interpret correctly the boulder indications. This applies particularly to a zone along the ice shed, where the directions of ice transport are very irregular, and in areas under the highest coastline. Following the ice age large parts of Fennoscandia were immersed below sea level, and later elevated above sea level, which elevation is still going on. On such an old sea bottom the tracing of boulders is rendered more difficult because of redeposition of moraine, boulder transport by drift-ice, and covering sediments. In the highlands exists another factor creating difficulties, namely solifluction, which is able to move the boulders out of their original position.

In the Skellefte district the first indications of new ore boulders were in most cases given by local inhabitants. They were aided by roadbuilding and ditching, which has also given excellent sections of the moraine. On the contrary, in the sparsely populated mountains local inhabitants only seldom have pointed out new ore boulders.

Tracing ore boulders is no universal method of prospecting, but suitably adapted to local conditions it has proved to be of great importance in Sweden. It constitutes an important stage in prospecting, which then, in order to be successful, requires an intimate cooperation between geologists and geophysicists.

BOLIDEN, SWEDEN,
August 1, 1953.

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DISCUSSION

ORIGIN OF THE SOFT IRON ORES OF MICHIGAN.

Sir: In a recent issue of this journal Mr. Mann [1] presents the results of a study of the soft iron ores of Michigan and concludes (p. 278): "Thus the soft ores of the Negaunee and Ironwood iron-formations must have originated by the action of hot hydrous solutions on silicated iron formations in the manner suggested by Gruner's modified hydrothermal theory." For the sake of the record, it seems worthwhile to point out that this view is not supported by all who work in the region and that certain inconsistencies are present in the article.

The two separate processes invoked—silication of an original chert-siderite rock, and hydrothermal oxidation and leaching of silica—must be considered separately, as it is possible to accept one and not the other. The first stated concept, that of silication of chert-siderite iron-formation, is by no means as general a phenomenon as implied by Mr. Mann (and earlier by Prof. Tyler). It is generally recognized that grunerite, the iron amphibole, is formed by metamorphic processes of intermediate to high intensity; this metamorphism is properly referred to as silication. But the soft ores are confined almost exclusively to areas of lower metamorphic grade, in which the principal silicates present are minnesotaite and stilpnomelane. The interbedding of these silicates with siderite and chert, in all proportions and all combinations, and the presence of the iron silicate greenalite as the dominant iron mineral in the completely unmetamorphosed Gunflint iron-formation of Ontario, is virtual proof that much of the iron silicate now found is either of primary origin, as held by Gruner (1946), or is derived by simple reorganization of silicate material of similar composition that is of primary origin. More extensive discussion of this point will be given by the present writer in a forthcoming paper in this journal.

The second concept—that of hydrothermal origin of the soft ores—is as strongly debated now as when first advanced by Gruner in 1930. One of Mr. Mann's chief contributions to this theory is based on analysis of mineralogical changes in dikes adjacent to ore bodies, and Mr. Mann concludes (p. 278): ". . . specific alterations of the dikes are explained only by hydrothermal activity." The dikes in question, according to the discussion, are altered to chlorite, sericite, talc, and kaolinite, and on p. 274 the statement appears: "Thus, of the four minerals common to the igneous rocks altered by the ore process, three are indicative of hydrothermal activity, and the other is formed in hydrothermal zones." (The last-mentioned mineral is

[1] Mann, Virgil I., 1953, The relation of oxidation to the origin of soft iron ores of Michigan: Econ. Geol., vol. 48, p. 251–281.

kaolinite.) But Mr. Mann has not given due recognition to the effects of pre-ore regional metamorphism. Regardless of whether the dikes lie in the vicinity of iron-formation or not, they have been metamorphosed to a greenschist facies. The chlorite and sericite have nothing to do with the process of ore formation; they are products of regional low-grade metamorphism that predates the development of ore in the iron-formations. The third mineral mentioned as being present is talc, with the quoted authority being the 1897 monograph by Van Hise and Bayley. The presence of this mineral in the altered rocks has not been verified by the present writer, and it has been general experience to find that "talc" was used loosely at that time without specific identification. The fourth mineral, kaolinite, is abundant, but certainly all will agree that this mineral is equally or more common as a product of weathering as it is of hydrothermal activity. It appears, then, that of the four minerals discussed, two have no necessary relation to the ore process, one may not be present at all, and the remaining mineral—kaolinite—is not critical.

The entire concept presented by Mr. Mann may be tested in the Iron River district of Michigan, where all the mines have been mapped in detail by the U. S. Geological Survey. In this area, it may be stated with a considerable degree of assurance that "silication" did not precede development of ore—as a matter of fact the only parts of the iron-formation that contain an iron silicate (here aphrosiderite) are characteristically barren of ore, whereas the adjacent chert-siderite rock may be completely altered to hematite and goethite. The ore occurs exclusively in "upward-facing" structures bottomed by a graphitic pyritic slate, and it has been possible to examine in detail the rock enclosing the ore bodies. The oxidation fades out gradually downward, and within a few feet below ore bodies of major size, the underlying rock is unoxidized, unaltered, and unbroken, without the slightest evidence of passage of "hydrothermal solutions." The present writer would not wish to defend all aspects of the Van Hise-Leith concept of origin of the soft ores—many features of the ore bodies are difficult to explain without appreciable modification of the theory—but the hydrothermal theory appears to have even greater weaknesses.

One further comment may be made. Mr. Mann mentions on p. 271–272 the quartz-pyrite veins in the ore, and concludes: "If the source of the pyrite was hydrothermal, it is likely that the source of the oxidizing solutions was also hydrothermal." It is well known that veinlets bearing pyrite, and many other minerals commonly thought to be of hydrothermal origin (such as chalcopyrite, bornite, magnetite, specularite, hausmannite, galena, sphalerite, and pitchblende), are found throughout the region, not only in the iron-formation but in the country rocks as well. Their presence frequently has been used as evidence to support the hydrothermal theory for formation of the soft ore. Actually, these minerals vein the soft ores that are clearly later on the basis of spatial relations. And according to a recent communication from L. P. Barrett, an age determination on pitchblende from one of the veins in soft ore indicates an Ordovician age, whereas the

soft ores themselves can definitely be established as having been formed before deposition of the sandstones of Cambrian age.

HAROLD L. JAMES

GEOLOGIST, U. S. GEOLOGICAL SURVEY,
IRON RIVER, MICHIGAN,
August 26, 1953.

GEOLOGIC IMPORTANCE OF STABLE ISOTOPIC ABUNDANCES.

Sir: I wish to comment on the article by M. L. Jensen in ECONOMIC GEOLOGY, vol. 48, No. 3, page 161 et seq., entitled "Geologic Importance of Variations in Stable Isotopic Abundances."

In discussing the helium isotope ratios on page 166 the author, I believe, omitted one observation that might be important in economic geology.

Some of the variations in the isotope ratio of helium are not too complex to explain and, I think, might interest your readers. Helium in the ground

EXPERIMENTAL WORK.

(By A. O. C. Nier and L. Aldrich.)

TABLE I.*

MINERALS CONTAINING URANIUM.

Sample	$He^3/He^4 \times 10^7$
No. 1	<0.2
2 Pitchblende	<0.3
3	<0.2
4	<0.2
5 Uraninite	<0.3

TABLE II.*

MATERIALS NOT CONTAINING URANIUM.

	$He^3/He^4 \times 10^7$
Nine mineral samples	2. –20. generally
Ordinary air	12.

TABLE III.*

FIELD SAMPLES IN UNITED STATES.

	$He^3/He^4 \times 10^7$
No. 1	0.5
No. 2	3.0
No. 3	5.0
No. 4	0.5
No. 5	0.5
No. 6	2.0
No. 7	1.5
No. 8	1.5
No. 9	1.0
No. 10	<2.5
No. 11	<2.0
No. 12	<1.0

THEORETICAL CALCULATIONS.

(U. S. Patent No. 2,551,499.)

TABLE IV.

CALCULATIONS FOR ONE PARTICULAR SITE.

U wt. fraction in ore		$He^3/He^4 \times 10^7$
3×10^{-7}		2.0
3×10^{-6}	Approx. normal distribution in earth's crust	2.0
3×10^{-5}		2.0
3×10^{-4}		2.0
3×10^{-3}	This concentration begins to be economic	1.8
3×10^{-2}		1.04
15×10^{-2}		0.31
27×10^{-2}		0.015

* Phys. Rev., Dec. 1, 1948, p. 1590, vol. 74, No. 11.

comes mostly from uranium deposits. The variation in isotope ratios from this helium is largely caused by variations in the *concentration* of uranium in the earth. Thus, helium-isotope-ratio measurements can be used to differentiate between rich and lean uranium ores by analyzing helium samples from the site—without ever sampling the ore.

The reason that variations in the uranium *concentration* cause variations in the *isotope ratio* goes as follows: Ore deposits release He^4 (as α-particles) and neutrons (from α-*n* reactions with the gangue material and from spontaneous fission). The neutrons are either captured in the gangue material making some He^3 (from lithium, etc.) or they are captured by uranium making no He^3. *Thus, if there is a large concentration of uranium there will be little* He^3 *formed and, therefore, a small* He^3/He^4 *ratio.* And vice-versa.

The enclosed Tables I, II, and III are abstracts from experimental work done by Dr. Nier and reported, as indicated, in the Physical Review. The Information in Table IV is taken from theoretical calculations made by using the hypothesis outlined above. In at least two cases the field samples taken by Nier, which give low ratios, have also given strong indications of neighboring uranium mineralization not previously discovered.

JOHN R. MENKE.

WHITE PLAINS, N. Y.,
September 1, 1953.

BANDED IRON FORMATIONS

Sir: Prof. Moore's little note on Banded Iron Formations (ECON. GEOL., 48 (4), p. 312) brings forth another comment from me.

The "banded iron formations" seem to yield some red-herrings—such as Moore's observations following his remark "This elaborate crumpling of such hard brittle rocks as those composing the iron formations has been a puzzle." Why a puzzle? In my early field days I remember having similar difficulties, but along the years of field mapping and looking down a microscope, instances of the relative mobility of quartz under pressure became so commonplace that the difficulty vanished. The fine crumpling is all the more readily understood in such finely laminated rocks, the laminae being nicely lubricated with iron oxide. Many more competent rocks than these have been equally closely crumpled. I don't see the need for fancy explanations of difficulties that don't exist concerning the folding of these rocks. From my field experience, one fact stands out—where the associated rocks are little folded, so also are the banded hematite quartzites, and where the associated rocks are highly folded and crumpled, so also are the banded quartzites.

Again, why is "Evidence of cross-cutting relations between silica and adjacent rocks something to be expected in replacement formations"? Silicification is notoriously selective. Even so, I have seen these banded quartzites fingering out into the related unsilicified material too often to ignore the field evidence, quite apart from the petrological evidence. Of course, the evidence of silicification may be just another red-herring obscuring another explanation, but so far no one has produced another explanation of the Indian occurrences,

which will stand up to any scrutiny. As I indicated in a previous communication, Spencer and Percival built up a series of hypotheses, lacking in stability, from evidence not one jot of which was a denial of replacement. In Canada, if it is so, as Prof. Moore believes, that Tanton is the only geologist holding the views stated, then perhaps that may be a cause for regret. My thoughts go back to a morning of long discussion on these rocks in Ottawa with that grand sincere geologist Collins, and then I can only say "Bravo Tanton!"

I am now out of touch with recent geological thought, but in the later years whilst still active in geological matters, I began to feel that geology was suffering from an accumulation of red-herrings. Maybe it might be to the good if geologists would treat their own work on its merits and get out of the habit of bolstering it with streams of references to the work of others. The written word seems to have a rare fascination for many, weakening their powers of discernment and logic.

I apologise if the following story seems to be unkind, but it will explain my inherent suspicion of theories on these "banded formations." About twenty years ago when I was functioning for a time as petrologist on the Geological Survey of India, someone (not an officer of the Survey) brought to the laboratory specimens and thin sections of a rock which he said was a lava (trachyte I think he called it). He said he was satisfied that the banded hematite quartzite was derived from this lava flow, and he had completed a paper on it; he wished to use the laboratory camera to take microphotos. I was, of course, greatly interested, put a thin section under the microscope which happened to have the nicols crossed, and commented on the high interference colours, which he attributed to the undue thickness of the section of "feldspar" laths. A minute or two later I suggested it would be advisable to revise his theory. The "feldspars" were grunerite, the rock a grunerite schist common enough in the area from which he had brought it.

J. A. DUNN.

TOORAK,
MELBOURNE, AUSTRALIA.
August 28, 1953.

REVIEWS

Depositi Minerari. By Antonio Cavinato. Pp. 883; figs. 90. Liberia Tecnica Editrice, Torino, 1952.

The composition, mineral association, and geologic and geographic distribution of metallic and non-metallic mineral deposits are briefly described in the 14 chapters comprising the book; representative foreign deposits and many Italian deposits are given as examples. In chapter one, Deposits of Magmatic Segregation, the author discusses diamonds and other precious stones, platinum, chromite, magnetite, corundum, and magmatic sulfides. Chapter two is devoted to pegmatite deposits. Deposits in Metamorphic Areas, chapter three, deals with contact metasomatic deposits and not with true metamorphic deposits. In chapter four, hydrothermal deposits are divided into three classes on the basis of temperature; high temperature deposits including those of molybdenite, cassiterite, wolframite, and auriferous quartz; intermediate temperature deposits of lead, zinc, copper, and silver sulfides; and low temperature deposits containing mercury, antimony, selenium, arsenic and tellurium minerals. Chapter five groups together the descriptions of asbestos, kaolin and talc. Chapter six is concerned with the zone of oxidation and cementation. Chapters seven and eight discuss the origin, geologic occurrence, geographic distribution, and world production of the mineral fuels, petroleum and coal. Biochemical, alluvial, evaporate and residual deposits are discussed in separate chapters. The metallogenic eras and provinces of Italy are described in chapter thirteen. The last chapter includes a discussion of the production and uses of many primary materials. The book was written primarily as a text for students and as a reference for mining engineers; as such it is unfortunate that more reference was not made to recent literature. It will prove most valuable for its many descriptions of Italian mineral deposits.

Frank G. Lesure.

Yale University,
New Haven, Conn.,
November 1, 1953.

Oil in the Soviet Union. By Heinrich Hassmann. Pp. 173; figs. 19; tbls. 43. Price, $3.75. Princeton University Press, Princeton, N. J., 1953.

Dr. Hassmann wrote this nontechnical book in Western Germany, and it was translated by Alfred M. Leeston, known for his *Magic Oil*, and other books. E. DeGolyer has written a foreword.

The author treats of the development of oil in Russia starting off in Part I, The Basis of the Russian Oil Industry, with the Russian economic system. In Part 2, he takes up the oil industry in the czarist regime and then the development of the Soviet oil industry, giving their use of geophysics, techniques, production, refining, exports and consumption. Part 3 deals with the oil and gas regions of the Soviet Union, of which 17 are described. These descriptions give the fields,

production, refining and transportation. The introduction to Part 3 gives some data on oil reserves. The translator's footnote gives a quotation from the Petroleum Press Service stating that reserves have risen from 7 billion barrels in 1938 to 30 billion barrels. Part 4 deals with the Soviet demand for oil, and the problems faced in the supply.

The author's appendix gives tables of oil production for the world, United States and Russia from 1861 to 1950 and for other oil-producing countries for 1948, 1949 and 1950. The translator's appendix gives similar figures for 1950, 1951 and 1952, and also three pages about the development of the "Second Baku," east of the Urals.

The book gives much information to anyone who wishes to be informed about Soviet oil and should also interest geographers and economists as well as geologists. The translator has done an excellent job, and his footnote comments are timely.

Japan's Natural Resources and Their Relation to Japan's Economic Future. By EDWARD A. ACKERMAN. Pp. 655; figs. 98. University of Chicago Press, 1953. Price, $25.00.

The material for this large authoritative tome was gathered by Professor Ackerman while he was technical advisor and visiting expert consultant to SCAP from 1946 to 1949, on leave as professor of geography at the University of Chicago. It is an enlargement and revision of his SCAP report of 1948.

The material of the book is based upon the author's own field studies and also contributions from many other staff members of the Natural Resources Section of SCAP, and upon SCAP reports and Japanese official documents.

The book is divided into three main parts: I, the Character of Resources and Requirements; II, the Possible Advances in the Efficiency of Reserve Use; III, Japan and the Western World; and 11 Appendices. Altogether there are 21 chapters. The first part deals with food, energy, fiber, construction materials, and minerals for construction and industrial uses. The second part, with 9 chapters, deals with increased production of minerals, forest products, fibers, fuels, fertilizers, water resources and development and improvements in resource use. The third part considers Japan's resource position of the near future in the main materials necessary for her economy. The last chapter takes up Japan's resource-management policy and problems of undeveloped areas. Eleven appendices give very much informational data and lists of reports dealing with Japanese resources.

For geographers and others interested in Far Eastern resources this volume provides a wealth of information.

Climate, Vegetation and Man. By LEONARD HADLOW. Pp. 288; illust. Philosophical Library, New York, 1953. Price, $4.75.

This delightfully written little book blends meteorology, geography and man's adaptation to different environments. Part I deals with simple astronomic features of the earth, climate and weather, temperatures, pressure belts, wind, rain, clouds and water movements. Part II treats of the relation between climate and vegetation. Part III consists of 12 chapters dealing with man's response to climate and vegetation in cool, cold, warm and hot belts. The book is well illustrated with pictures and charts and should serve as a pre-college text book or for the interested lay reader.

Modern Uses of Nonferrous Metals. EDITED BY C. H. MATHEWSON. Pp. 530; illust. American Institute of Mining and Metallurgical Engineers, New York, 1953. Price, $7.00 to non-members; $4.90 to members.

This volume is a revision under the editorship of C. H. Mathewson, Emeritus Professor of Metallurgy at Yale, of an earlier Seely W. Mudd volume that appeared in 1935 and underwent six printings.

Thirty-three outstanding authors have contributed entirely new chapters to bring the material up to date. So many changes in the use of metals have taken place since 1935 that this new volume will be welcomed by both technical and non-technical readers. The chapters are written in non-technical language and many in narrative form. The book is a storehouse of knowledge on the uses of 31 of the commonly used metals.

BOOKS RECEIVED.

FRANK G. LESURE.

Reconnaissance in the Western Part of the Trans-Pecos Region of Texas. JONATHAN P. HADFIELD, JR. Pp. 15; pl. 1; figs. 2. U. S. Atomic Energy Commission, RME-4021, Oak Ridge, Tenn., 1953.

Index to Publications of the Colorado School of Mines. Pp. 89. Colorado School of Mines, Golden, 1953. *Lists all publications including prices of those still available.*

Illinois State Geological Survey—Urbana, 1953.

Rept. of Inv. 162. Geologic Aspects of Radio Wave Transmission. M. WILLIAM PULLEN. Pp. 73; figs. 41. *Report on preliminary investigations of features that affect radio field intensity in ground-wave areas at standard broadcast frequencies. Indicates that geologic conditions cause some signal intensity anomalies.*

Illinois Petroleum Ser. 68. Developments in Illinois and Indiana in 1952. ALFRED H. BELL AND DONALD G. SUTTON. Pp. 1301–1314; fig. 1; tbls. 10.

Forty-First Annual Report. Pp. 42. Office of the State Inspector of Mines, Albuquerque, New Mexico, 1953.

North Dakota Geological Survey—Grand Forks, 1953.

Circ. 21, 23–25. Pp. 21. *Logs of following well: Continental—P. H. McCay No. 1; Evans Prod. Co.—Johnson No. 1; Hunt Oil Co.—Peter Lenertz No. 1; Samedan Oil Co.—Vaughn Hanson No. 1.*

Rept. of Inv. 2, revised 1953. Stratigraphy of North Dakota with Reference to Oil Possibilities. WILSON M. LAIRD AND DONALD F. TOWSE. 2 sheets; figs. 13; tbl. 1.

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1953.

Bull. M37. Oil and Gas Developments in the Appalachian Basin Past and Present. CHAS. R. FETTKE. Pp. 69–83; pl. 1; figs. 2; tbl. 1.

Progress Rept. 142. Geologic Structure of Parts of the Chestnut Ridge and Driftwood Anticlines in Clearfield and Elk Counties, Pa. ROBERT C. BOLGER. 1 sheet. *Structural contour map-scale 1 to 62500 and brief description of geology.*

Geology of the Silver Reef (Harrisburg) Mining District, Washington County, Utah. PAUL DEAN PROCTOR. Pp. 169; pls. 11; figs. 13; tbls. 8. Utah Geological and Mineralogical Survey, Salt Lake City, Bull. 44, 1953. Price, $2.00. *Silver, copper, uranium and vanadium minerals believed concentrated by ground water in channel deposits rich in organic matter.*

Plane Table Manual for Geologists. KENNETH K. LANDES. Pp. 17. George Wahr Publ. Co., Ann Arbor, Mich., 1951. *Rules and cautions for triangulation and Beaman stadia traverse; written to supplement standard manuals.*

Pre-Cornell and Early Cornell I. Studies in History No. 15. ALBERT HAZEN WRIGHT. Pp. 51, pls. 2. A. H. Wright, 113 E. Upland Rd., Ithaca, N. Y. Price, $1.35. *Contains many notes and letters of Louis Agassiz dealing with Cornell history.*

Pre-Cornell and Early Cornell II. Studies in History No. 16. ALBERT HAZEN WRIGHT. Pp. 60; pls. 2. A. H. Wright, 113 E. Upland Rd., Ithaca, N. Y. Price, $1.35. *Contains numerous letters to C. F. Hartt; of historical interest.*

Bituminous Coal Annual, 1952. Pp. 176; figs. 42; tbls. 64. Bituminous Coal Institute, Southern Building, Washington 5, D. C. *Statistical data for 1951–52.*

Ontario Department of Mines—Toronto, 1953.

Vol. LXI, Pt. 1. 61st Annual Report. Pp. 97; tbls. 8.

P. R. 1953–1. Preliminary Report on Ground Investigations of Aeromagnetic and Aeroradioactive Anomalies in the Espanola-Lake Huron Area. W. D. HARDING. Pp. 9; figs. 2; tbl. 1.

The Australian Mineral Industry, Vol. 5, No. 4. Pp. 93–134. Bureau of Mineral Resources, Geology and Geophysics, Melbourne, 1953.

Departomento Nacional da Produção Mineral do Brasil—Rio de Janeiro, 1950–52.

Bol. 87. Relatório da Diretoria, 1948. Pp. 217.

Bol. 88. Arqui-Brasil e sua Evolução Geologica. DJALMA GUIMARÃES. Pp. 319; figs. 37.

Bol. 91. Camadas de Carvão Mineral e seu Comportamento no sul de Santa Catarine. HANNFRIT PUTZER. Pp. 182. *Extensive study of Lower Gondwana coal beds in southern Brazil.*

Bol. 92. Higiene das Minas de Carvão do Estado de Santa Catarina. MANOEL MOREIRA. Pp. 54; pls. 2.

Bol. 93. Relatório da Diretoria, 1950. Pp. 160.

Bol. 138. Contribuição à Geologia do Município de Olinda, Pernambuco. PAULO ERICHSEN DE OLIVIERA AND JOSÉ R. DE ANDRADE RAMOS. Pp. 24; figs. 9.

Bol. 139. Considerações Sôbre o Arenito Caiuá. EVARISTO PENNA SCORZA. Pp. 62; figs. 30.

Relatório Anual do Diretor, 1951. Pp. 60.

Notas Preliminares e Estodus, Nú. 54. Plantas Triássicas sul do Brasil. MACKENSIE GORDON, JR. AND ROLAND W. BROWN. Pp. 6; pl. 1.

Notas Preliminares e Estudos, Nú. 55. Contribuição para o Conhecimento de Alethopteris Branneri White. W. GOTHAM AND W. J. JONGMANS. Pp. 12; pls. 3.

Notas Preliminares e Estudos, Nú. 56. Sobre a Formacai Piauí (Carbonífero Superior) no Araguaia. WILHELM KEGEL. Pp. 7; fig. 1.

Notas Preliminares e Estudos, Nú. 57. Bibliografia sôbre as Aplicações do Microscópio Eletrônico ao Estudo de Argilas. PERSIO DE SOUZA SANTOS AND HELENA LOPES DE SOUZA SANTOS. Pp. 11.

Minas Gerais Instituto de Tecnologia Industrial—Belo Horizonte, 1949–53.

Avulso No. 10. Estudo Químico da Apatita de Araxá. L. MENICUCCI SOBRINHO. Pp. 15.

Avulso. No. 11. Encore à propos de la Genèse des Orthopyroxènes. DJALMA GUIMARÃES. Pp. 20; pls. 3; figs. 5.

Avulso No. 12. Separação e Determinação Gravimétrica do Tungstenio em Minerais e Ligas. FERNANDO PEIXOTO. Pp. 15.

Avulso No. 13. Radioatividade e Fertilização. WILLER FLORÊNCIO. Pp. 10.

Avulso No. 13. Carte des Directions de Cisaillements dans le Brésil Centre-Est. B. BRAJNIKOV. Scale—1 : 2,000,000.

Bol. 11. Minerais de Urânio e Thório. WILLER FLORÊNCIO. Pp. 137. *Lists minerals containing uranium or thorium, giving properties, formula and occurrence.*

Bol. 12. Prática de Analise de Rocha. MARYSIA FONTOURA LEINZ. Pp. 97; tbls. 3.

Pub. 1. Problemas de Cronogeologia. F. PEIXOTO AND D. GUIMARÃES. Pp. 35; pls. 9; tbls. 8. *Study of the effect of weathering on some uranium and thorium minerals.*

Universidade de São Paulo Faculdade de Filosofia, Ciências e Letras—São Paulo, 1953.

Bol. 159, Min. 11. Petrologia da Região de São Roque, São Paulo. JOSÉ MOACYR VIANNA COUTINHO. Pp. 80; figs. 20. *Petrographic study of Precambrian para-metamorphic rocks and pre-Devonian granites near São Roque.*

Bol. 163, Min. 12. Sôbre Figuras e Canais de Corrosao em Spodumênio do Brasil. JOÃO E. SOUZA CAMPOS; **Determinação de Índices de Zona no Sistema Hexagonal.** WILLIAM G. R. DE CAMARGO; **Scolecita, Rio Pelotas, RS.** RUI R. FRANCO; **Trifilita de Picuí, Paraiba, Brasil.** RUI R. FRANCO, MURILLO C. PORTO E BENEDICTO A. FERREIRA. Pp. 40.

Orville A. Derby's Studies on the Paleontology of Brazil. EDITED BY ALPHEU DINIZ GONSALVES. Pp. 162; pls. 9; figs. 5. Published under the direction of the Executive Commission for the Ist Centenary Commemorating the Birth of Orville A. Derby, and sponsored by the American Embassy in Brazil, Rio de Janeiro, 1952. *Eight important papers on the Paleontology of Brazil, published in English as a memorial to O. A. Derby.*

Minerales—Santiago de Chile, 1953.

Ano VIII, N. 43. Pp. 43.

Ano VIII, N. 44. Pp. 44–82.

Mikroskopischer und spektrographischer Beitrag zur Frage der Entstehung einiger Kolloidalstrukturen von Zinkblende und Wurtsit. JAN KUTINA. Pp. 436–452; pls. 16. Zeitschr. Geologie, Jahr. 1, Heft 6 S, Akademie-Verlag, Berlin, April, 1953.

Mineralbestand, Strukturen und Genesis der Rammelsberg-Lagerstätte. PAUL RAMDOHR. Pp. 367–494; figs. 154. Geol. Jahr., Band 67, Hannover, February, 1953. *Detailed study of mineral content, structure and texture of ores.*

The Diamond Tool Industry in 1952. Pp. 8; tbl. 1. Industrial Diamond Information Bureau, 32–34 Holborn Viaduct, London, EC1, March, 1953. *Survey of diamond tool industry, includes information on hardness, wear and abrasion testing, shaped diamond tools, diamond truing tools and rock drilling.*

Industrial Diamond Trade Names Index and Yearbook for 1953. Pp. 84. Industrial Diamond Information Bureau, 32–34 Holborn Viaduct, London, EC1, 1953. Price, 3/6d. *Lists 1900 trade names of manufacturers of diamond tools and abrasives.*

Osservazioni geologiche nelle zone minerarie dell'Isola d'Elba. A. DEBENEDETTI. Pp. 35; figs. 8. Boll. del Servizio Geologico d'Italia, Vol. LXXIV, Roma, 1953.

Geological Survey of Japan—Hisamoto-chō, Kawasaki-shi, 1953.

Rept. 153. Albitite and Associated Jadeite Rock from Kotaki District, Japan: A Study in Ceramic Raw Material. SHUICHI IWAO. Pp. 25; pls. 7; figs. 11; tbls. 7.

Rept. 154. Mercury Deposits in Japan. SUMIO HORI. Pp. 132; figs. 41. *Detailed descriptions of distribution and genesis, history of mining, production and reserves of all mercury deposits in Japan.*

Rept. 155. Variation of Crystal Habit of Calcite. ICHIRO SUNAGAWA. Pp. 71. *Changes in crystal habit of calcite thought to be qualitative indications of temperatures of formation.*

Rept. 156. Studies on Seismic Reflection Method. TETSUICHI KANEKO. Pp. 43; figs. 38.

Bull., Vol. 4, Nos. 1–6. *Many short papers of general interest, each with an English abstract.*

Explanatory Text and Geological Map of Japan. Kayanuma (Sapporo-18). MASATSUGU SAITO, FUJIO UEMURA AND ATSUSHI OZAWA. Pp. 58; figs. 4; tbls. 6. Scale 1:50,000.

Geologic Map of Tokushima. Scale, 1:75,000.

Coal Fields of Japan. *One sheet with charts and tables giving age, index of coking property, production and imports of coal. One map, scale 1: 2,000,000 of coal fields in Japan, 4 maps, scale 1: 400,000 of geology of important coal fields.*

Guide-Book of Excursion. Regional Conference on Mineral Resources Development, Economic Commission for Asia and the Far East, Tokyo,

April 20–May 10, 1953. Pp. 38; figs. 9. *Descriptions covering geology, mining methods, production and reserves of Yanahara pyrite mine, Besshi copper mine, Ube coal field and Miike colliery.*

Institute of Geology and Paleontology, Tohoku University, Sendai, 1952–53.

Special Vol. No. 3. Science Reports, Second Series (Geology). Pp. 464.

Contr. No. 42. Intraformational Abnormal Deposition Observed in the Kameno-o Formation. JUN-ICHI IWAI. Pp. 22; pls. 3; figs. 16. *Intraformational corrugation believed to be caused by subaqueous sliding and associated mudflows and turbidity currents.*

Contr. No. 43. Geology of the Shintotsukawa District, Kabato-gun, Ishikari Province, Hokkaide. SHIGERU IMANISHI. Pp. 41; pls. 2; figs. 9.

Société Chérifienne des Pétroles, L'Année 1952. Pp. 72. Rabat, 1952. *Brief description of the petroleum industry in Morocco.*

Estudos, Notas e Trabalhos, Vol. VII, Fasc. 1–2. Pp. 286. Servico do Fomento Mineiro, Porto, Portugal, 1952.

Sierra Leone Geological Survey—Freetown, 1950–51.

Annual Rept. for the Year 1950. Pp. 13. Price, 1s.

Annual Rept. for the Year 1951. Pp. 14. Price, 1s. 6d.

Ministero de Minas e Hidrocarburos—Caracas, 1952–53.

Revista de Hidrocarburos y Minas, Ano II, Núm. 8. Pp. 247.

Revista de Hidrocarburos y Minas, Ano II, Núm. 9. Pp. 192.

Revista de Hidrocarburos y Minas, Ano IV, Núm. 10. Pp. 356. *Mining, petroleum and economic activities for 1952.*

Actividades Petroleras. Ano V, Nos. 102–103. Pp. 48. *Drilling, production and refining data.*

Pétrographie des Roches Sédimentaires. ALBERT CAROZZI. Pp. 258; figs. 27. F. Rouge & Cie S. A., Libraire de l'Université, Lausanne, 1953. Price, 23.40 frs. *Part I discusses the detrital, chemical, precipitate and authigenic mineral constituents of sedimentary rocks; Part II divides detrital rocks into conglomerates, breccias, sandstones, and argillites and describes the formation of each; Part III describes under the heading, bio-chemical rocks, carbonate, siliceous, ferruginous, phosphatic, saline and carbonaceous sedimentary rocks.*

Historical Aspects of Organic Evolution. PHILIP G. FOTHERGILL. Pp. 427; figs. 6; tbls. 9. Philosophical Library, New York, 1953. Price, $6.00. *Divided into two sections: an historical survey of evolutionary theories from Aristotle to the present, and a summary of the modern casual theories of organic evolution.*

Gold—Die Metallischen Rohstoffe, Heft 3. FERDINAND FRIEDENSBURG. Pp. 234; figs. 30; tbls. 98. Ferdinand Enke Verlag, Stuttgart, 1953. Price, paper DM 30; cloth DM 33. *Part one is a detailed account of the occurrence and origin of gold deposits; mining, ore-dressing, refining and uses of gold; history of gold; marketing, production and future reserves of gold. Part two is a study of gold deposits and mining areas in the world arranged by countries.*

Directory of Indian Mines and Metals. P. K. GHOSH. Pp. 208. Mining, Geological and Metallurgical Institute of India, New Delhi, 1952. *Gives essential data concerning 3,000 producing mines and quarries covering the most important metallic and non-metallic minerals.*

Mineral Forecast 2000 A.D. EDWARD STEIDLE. Pp. 216; figs. 7. Pennsylvania State College, State College, Pa., 1952. *Discussion of the problems that the mineral industries must solve, including mineral shortages, conservation, technology and education.*

Mineralien und Lagerstätten in Ostbayern. HUGO STRUNZ. Pp. 128; figs. 77. Gustav Bosse Verlag, Regensburg, 1953. Price, DM 9.80. *Descriptions of many deposits in East Bavaria; good bibliography for each deposit.*

This Earth of Ours Past and Present. C. WROE WOLFE. Pp. 374; figs. 235. Earth Science Publishing Co., Revere, Mass., 1953. *Many illustrations too small and poorly reproduced.*

SCIENTIFIC NOTES AND NEWS

R. H. B. JONES has been appointed consulting geologist for the Oliver Iron Mining Division. He has been with Oliver since 1930.

MERLE H. GUISE, consulting mining engineer, has recently returned to New York from a trip to the Territory of Amapa, Brazil, where he had been examining tin, tantalite, and columbite deposits.

PAUL F. ARMSTRONG, Canadian mining geologist, is assisting the Turkish government with its field work in evaluating ore deposits, particularly chromite, lead, zinc, and is prospecting for new mineral reserves.

JACOB FREEDMAN, U. S. Geological Survey, is now in Israel where he will make a general reconnaissance of mineral resources and appraise deposits for possible commercial development.

WILLIAM E. WRATHER, past president of the American Institute of Mining and Metallurgical Engineers, and director of the U. S. Geological Survey, has been awarded the John Fritz Medal by unanimous choice of a 16-man board. The medal is given annually for notable scientific or industrial achievement. In awarding the medal to Dr. Wrather, the board cited him as: "A geologist of worldwide experience and fame; an outstanding scientist and historian; a wise leader distinguished for his service to the nation."

The Thirtieth Annual Meeting of the PACIFIC SECTION OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, SOCIETY OF EXPLORATION GEOPHYSICISTS, and the SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS was held at the Biltmore Hotel, Los Angeles, on November 5th and 6th, 1953.

DR. EDSON S. BASTIN passed away Friday morning, October 9th, 1953, following a short illness.

JAMES G. MCCREA, onetime chief geologist at the Dome Mine and subsequently vice-president of the Dome Mines, Ltd., as well as general manager of several Dome subsidiaries, died on September 12, 1953, at his home in Toronto of heart complications following an attack of pneumonia.

A. R. SMITH, formerly research geologist with International Nickel Co., is now with New Jersey Zinc Co. at Mineral, Va.

ROBERT HART is manager at the Quirk Lake development for Algom (sic) Uranium Mines, with headquarters at Algoma, Ontario.

ROBERT GREENWOOD has returned to the United States after several years in Brazil where he was associated with Proberil, S. A., in connection with industrial minerals. He is now at the Michigan College of Mines and Technology substituting for A. K. SNELGROVE who has accepted a Fullbright Award to Hong Kong.

GEORGE KENNEDY has resigned his position at Harvard University to undertake research work at the Institute of Geophysics at the University of California at Los Angeles.

FRANCIS CAMERON and W. F. JAMES have been elected to the board of directors of the Brunswicj Mining and Smelting Co. following a merger of three mining groups in the newly developed Bathurst field, New Brunswick.

THE NATIONAL CLAY MINERALS COMMITTEE, with the University of Missouri and the State Geological Survey of Kansas held its Second National Conference on Clays and Clay Minerals at the University of Missouri, Columbia, Mo., October 14–17, 1953.

THE ARIZONA GEOLOGICAL SOCIETY announces that it has sponsored reprinting of the following report: "Report on studies of stratification in modern sediments and in laboratory experiments" by Edwin D. McKee, Office of Naval Research, Project Nonr 164 (00), Nr-081-123. This report constitutes a record of characteristic types of stratification as found today in certain environments of deposition such as beachesm dunes, alluvial fans, lagoons, and tidal flats. The report also includes the results of laboratory experiments on the development of various kinds of stratification. It includes 61 pages, 12 plates and 28 text figures. Copies can be obtained at $1.00 each, postpaid, by sending a remittance to: Arizona Geological Society, P.O. Box 2270, Tucson, Arizona.

INDEX TO VOLUME XLVIII

[NOTE.—In this index the titles of principal papers and headings of departments, as *Discussions,* are in italics.]

Abstracts—
Accumulation of minor-elements in coal ash and its economic implications (Stadnichenko), 332
Acetonic dithizone in geochemistry (Warren, Delavault, and Irish), 306
Alteration associated with ore at Gaspe Copper Mines (Bell and Scott), 616
Application of geology to the discovery of zinc-lead ore in the Wisconsin-Illinois-Iowa district (Agnew), 322
Approaches to the study of lead-zinc gossans (Kelly), 622
Base metal deposits of northern New Brunswick (Mackenzie), 624
Beryl deposits in the Harding pegmatites, Taos County, New Mexico (Jahns and Adams), 328
Biogeochemical investigations in Finland (Marmo), 211
Cobalt-arsenic minerals associated with aplites at Cobalt, Ontario (Sampson and Hriskevich), 628
Commercial synthesis of star sapphires and star rubies (Frondel), 325
Comparison of megascopic and microscopic examinations of coals (Somers), 628
Copper shales of Germany and Michigan (White), 631
Coppermine River area, Northwest Territories, Canada (Jenney), 621
Definition of a mineral belt in south central Colorado (Gabelman), 177
Deposition of high temperature nonmagmatic magnetite (Holser and Schneer), 620
Dimension stone in the United States in 1952—A summary (Deiss), 324
Dimension stone industry of California (Norman), 330
Distribution of uranium deposits in the Shinarump conglomerate of the Colorado Plateau (Finch), 619
Domestic graphite supply problem (Cameron), 323
Emerald, Feeney and Dodger tungsten ore-bodies, Salmo, British Columbia (Ball), 615
Engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada (Legget and Bartley), 513

Abstracts—Continued
Field method for the determination of titanium in rocks (Shapiro and Brannock), 282
"Fossil" geochemical anomaly near Jerome, Arizona (Huff), 327
Fracture pattern and uranium ore of the Zuni Uplift, New Mexico (Bucher and Gilkey), 617
Genesis of California talc (Wright), 333
Geochemical association of niobium (columbium) with titanium and its economic significance (Fleischer), 324
Geochemical prospecting for copper at Ray, Arizona (Clarke), 39
Geochemistry and origin of the gold-bearing quartz veins and lenses of the Yellowknife greenstone belt, Northwest Territories, Canada (Boyle), 617
Geologic associations of niobium in the United States (Kaiser), 622
Geologic character of typical pitchblende veins (Everhart and Wright), 77
Geologic importance of variations in stable isotopic abundances (Jensen), 161
Geology and geochemistry of base metal deposits (Wilson), 370
Geology and ground-water conditions in the lower valley of the Rio Elqui of Chile (Jones), 457
Geology and ore controls at the Guadalupe mine, Nuevo Leon, Mexico (Whiting), 631
Geology and ore deposits of the central portion of the Labrador Peninsula (Staff of Iron Ore Co. of Canada), 625
Geology by Campbell Red Lake Mines Limited [Ontario] (Jarvis), 621
Geology of coal in Alberta (Crockford), 618
Geology of the Mindamar mine, Stirling, Nova Scotia (Richardson), 627
Geology of the Radium Hill Uranium mine, South Australia (Parkins), 626
Grading of natural corundum ores (Carl, White, and Hockman), 323
Half century of dimension granite quarrying in Massachusetts (Fletcher and Mould), 325
Hydrothermal rock alteration at Wairakei, New Zealand (Steiner), 1

Abstracts—Continued
Iron deposits of the Congonhas district, Minas Gerais, Brazil (Guild), 639
Iron ore at Bomi Hill, Liberia (Fitzhugh), 431
Jersey Dodger lead zinc ore bodies, Salmo, B. C. (Whishaw), 630
Lithologic ore controls in sandstone type uranium deposits, Colorado Plateau (Wright), 632
Metamorphic differentiates in the Blackbird mining district, Lemhi County, Idaho (Roberts), 447
Metamorphism of coal by peridotite dikes in southern Illinois (Clegg), 618
Methods used in geochemical prospecting analytical laboratory (Bloom), 322
Mining and milling of lithium pegmatites at Kings Mountain, North Carolina (Goter, Hudspeth, and Rainey), 326
Molybdenum bearing granite and granodiorite, Rautio, Finland (Marmo and Hyvarinen), 704
Monazite deposits of the southeastern Atlantic States (Mertie), 330
Morton granite gneiss (Lund), 46
Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions (Phair and Levine), 358
Notes on the silica problems of the bed rock ore deposits (Schmitt), 628
Occurrence, distribution and weathering of pyrite in coals from the Sydney coalfield, Nova Scotia (King), 623
Ore textures of uraninite and associated minerals from the Colorado Plateau uranium deposits (Miller), 625
Origin of alunite deposits at Pidinga, South Australia (King), 689
Origin of the chromite deposits of the Bay of Islands igneous complex, western Newfoundland (Smith), 408
Outbursts in coal mines (Ignatieff), 620
Paragenesis of the zinc-lead-copper deposits at the Mindamar mine, Nova Scotia (Watson), 630
Pegmatitic lithium deposits of Canada (Rowe), 627
Petrographic examination of washed, screened, and crushed samples of coal from the Sydney and St. Rose coalfields, Nova Scotia (Hacquebard and Lahiri), 619
Petrology of the Salem limestone (Indiana building stone) (Patton), 331
Polarization figures and rotation properties as applied to the identification of some cobalt nickel sulfarsenides and related minerals (Hutchinson), 492
Polishing phenomena in the copper sulfides (Wandke), 225
Abstracts—Continued
Qualitative color test for rapid identification of the clay mineral groups (Hambleton and Dodd), 139
Quarry practices in the Indiana building stone industry (Letsinger), 329
Radioactive, pronouncedly differentiated pegmatite sill, Lac La Ronge district, northern Saskatchewan (Mawdsley), 624
Radioactivity of rivers and lakes in parts of Garland and Hot Spring Counties, Arkansas (Arndt and Kuroda), 551
Reconnaissance of superficial phosphate deposit near Minas, Uruguay (Eckel and Milton), 437
Relation of oxidation to the origin of soft iron ores of Michigan (Mann), 251
Relation of pH and oxidation potential to sedimentary iron mineral formation (Huber and Garrels), 337
Review of physico-chemical data on the state of supercritical fluids (Smith), 14
Review of the Falconbridge ore deposit (Lochhead), 623
Rock bursting and other geologic problems in the granite quarries at Barre, Vermont (Jahns), 328
Significance of Pleistocene deposits in the ground-water resources of Illinois (Foster), 568
Sketch of the geology and ore deposits of Baja California, Mexico (Wisser), 333
Some biogeochemical investigations in eastern Canada (Warren and Delavault), 629
Some considerations regarding liquid inclusions as geologic thermometers (Skinner), 541
Some geologic features of a potash deposit (Jones), 329
Some recent American developments in geochemical prospecting for minerals (Hawkes), 327
Sources of error in the measurement of rotation properties with the ore microscope (Cameron, Hutchinson, and Green), 574
Steatite deposits of Bheraghat, Jabalpur district, M. P., India (Chhibber), 53
Structural and decrepitation features of the gold mineralization at the O'Brien mine, Quebec (Blais), 616
Structural conditions in coal mines of the southern Canadian Cordillera (Norris), 625
Structural setting of the Coeur d'Alene mining district, Idaho-Montana (Wallace and Hobbs), 629
Study of lead sulfide solubility and its relation to ore deposition (Hemley), 113

Abstracts—Continued
Textural pattern of the serpentines (Nagy), 591
Tracing of glacial boulders as an aid to ore prospecting in Sweden (Grip), 715
Ulvöspinel and its significance in titaniferous iron ores (Ramdohr), 677
Use of geology in developing the Blackbird cobalt-copper deposits, Idaho (Vhay), 332
Variation of low temperature decrepitation of quartz from the No. 6 vein of the Lamaque gold mine, Quebec (Smith), 628
Wall rock alteration in northwestern Quebec (Price), 626
Water soluble salts in limestones and dolomites (Lamar and Shrode), 97
Acetonic dithizone in geochemistry (Warren, Delavault, and Irish), 306
Ackerman, E. A., review of book by, 732
Activity coefficients of ionic strength, 117
Adularia, 6
Africa, East Africa, mineral resources (review), 65
Agnew, A. F., abstract by, 322
Ahrens, L. H., on copper, 380
on ionic radii, 148
Air, oxygen, isotopic abundances, 170
Alaska, Aleutian Islands, extrusives, titania content, 286
Alberta, coal (abstract), 618
structure (abstract), 625
Albitization, 712
Aldrich, H. R., on iron, 257
Aldrich, L. T., and Nier, A. O., on helium, 166
Allen, E. T., on solutions, 12
Allen, E. T., and Day, A. L., on solutions, 9
Allen, E. T., Crenshaw, J. L., and Johnson, J., on pyrite, 10
Allen, J. E., on chromite, 378
Allen, R. O., and Barrett, L. P., on iron, 257
Allgeier, R. J., Mafford, B. C., and Juday, C., on lakes, 354
Alling, H. L., on iron, 338
Alsifilm, 303
Alteration, Blackbird district, Idaho, 450
Bonanza district, Colo., 195
copper-nickel sulphide deposits, 388
dikes, Michigan, iron districts (discussion), 726
Gaspe Copper Mines, Que. (abstract), 616
hematite in pitchblende veins, 92
itabirite, Brazil, 672, 673
pitchblende deposits, 79, 89
Quebec, wall-rock alteration (abstract), 626
siderite-cherts, Michigan, 261
Alteration—*Continued*
tungsten deposits, France (review), 63
Salmo tungsten district, British Columbia (abstract), 615
uranium deposits, Colo. Plateau (abstract), 625
Yellowknife greenstone belt, Northwest Territories (abstract), 617
Alteration at Wairakei, New Zealand, Hydrothermal rock (Steiner), 1
Aluminum, oxides and hydroxides (review), 317
Alunite, 5
Alunite deposits at Pidinga, South Australia, Origin of (King), 689
Amphibole, 645
atomic structure, 374
Analcite, 6
Anatase, 297
Anderegg, F. O., and Peffer, H. C., on sulphates, 98
Andersen, O., on anorthite-forsterite-silica, 411
Anderson, N. S., and Delsasso, L. P., on carbon dioxide, 22
Angle of apparent rotation, 575
Antevs, E., on varves, 517
Antigorite, 591
Antimony, Italy, Gruppo dei Monti Romani (review), 315
Antonoff, G., on water, 19
Antonoff, G., and Conan, R. J., on sulphur, 19
Antonoff, G., Urmanczy, A., and Yakimac, A., on liquids, 19
Apatite, 9, 147, 260, 379, 438
Aphrosiderite, 261, 264
Aplites, cobalt-arsenic minerals, Cobalt area, Ont. (abstract), 628
Apparatus for determining titanium, 283
Aquifers, hydraulic characteristics, Rio Elqui valley, Chile, 477, 487
Arizona, Geochemical prospecting for copper at Ray (Clarke), 39
geochemical anomaly, Jerome area (abstract), 327
uranium, Shinarump conglomerate deposits (abstract), 619
Arkansas, Radioactivity of rivers and lakes in parts of Garland and Hot Spring Counties (Arndt and Kuroda), 551
Armstrong, A. T., on alunite, 693
Arndt, R. H., and Kuroda, P. K., *Radioactivity of rivers and lakes in parts of Garland and Hot Spring Counties, Arkansas*, 551–567
Arsenic, Cobalt area, Ontario (abstract), 628
Arsenides, radioactive ores, Great Bear Lake, N. W. T., 367
Arsenopyrite, 87, 493, 498, 718
Aruja, E., on antigorite, 591
Asbestos, 302

Assaying, ores and saltpeter (review), 505
Atack, D., and Schneider, W. G., on liquids, 18
Attapulgites, 142
Austin, J. B., on iron oxides, 276
Austin, J. B., and Day, M. J., on iron oxides, 277
Australia, South Australia, alunite, Pidinga deposits, 689
Radium Hill uranium mine (abstract), 626
Western Australia, alunite, analysis, Lake Campion, 694
Ayres, V. L., on nontronite, 275
Azimuth of vibration, 574

Babbit, E. C., on Marion mine, Colo., 193
Bacteria, iron deposition, Brazil, 640
Bagg, R. M., on Rito Alto district, Colo., 204
Bailey, S. W., and Cameron, E. N., on inclusions, 541
Bailey, Sir Ed., review of book by, 606
Bain, G. W., on Shinkolobwe mine, Belgian Congo, 78
Bainbridge, K. T., and Nier, A. O., on nitrogen, 168
Ball, C. W., abstract by, 615
Bancroft, D., on thyratron circuit, 544
Bandy, M., on metallization, 136
Barbosa, O., on itabirite, 641
Barite, 79, 631
Barnes, V. E., and Flawn, P. T., gravity survey, Van Horn area, Texas (review) 504
Barnes, W. H., on critical point, 21
Barrandite, 445
Bartley, M. W., with Legget, R. F., *An engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada*, 513
Basset, J., and Dodé, M., on nitrogen, 16
Bastin, E. S., on nickel-cobalt-silver ore deposits, 77
Bastin, E. S., and Hill, J. M., on Front Range district, Colo., 88
on water, 359
Bateman, A. M., on chloritization, 274
on ores, 400
reviews by, 313, 421, 422
Bateman, J. D., on chromite, 411
Bates, T. F., and Mink, J. F., on antigorite, 591
Bates, T. F., Sand, L. B., and Mink, J. F., on chrysotile, 591
Baxter, G. P., and Alter, C. M., on Shinkolobwe mine, Belgian Congo, 78
Bay of Islands igneous complex, western Newfoundland, Origin of the chromite deposits of the (Smith), 408
Bayliss, N. S., *et al.*, on alunite, 697
Becke, F., on myrmekite, 711
Becker, G. F., on sediments, 420
Belgian Congo, pitchblende, uranium content, 362
Shinkolobwe mine, 78
Bell, A. M., and Scott, F. J., abstract by, 616
Bentonite, Puerto Rico, Aguada deposit (communication), 239
Benz, C. A., and Stewart, G. W., on liquids, 18
Benzidine test for montmorillonoids, 143
Berek, M., on surface film, 588
Berg, L. G., on dolomite, 98
Bernal, J. D., and Fowler, R. H., on liquids, 18
Berry, J. A., on chalazoidite, 3
Beryl, helium content, isotopic ratios, 166
New Mexico, Harding pegmatites (abstract), 328
Beutell, A., on marcasite, 293
Beyschlag, F., Vogt, J. H. L., and Krusch, P., on cobalt, 394
Bheraghat, Jabalpur district, M. P., India, Steatite deposits of (Chhibber), 53
Bibliography, acetonic dithizone reagent use, 311
alteration, Wairakei, New Zealand, 13
alunite, Pidinga area, South Australia, 702
biogeochemical prospecting, Finland, 223
boulders and ore prospecting, Sweden, 725
carbon isotopic abundances, 602
chromite, Bay of Islands complex, Newfoundland, 415
cobalt-nickel sulfarsenides, optical properties, 500
color tests for clay minerals, 146
fluids, supercritical states, 34
geochemical prospecting for copper, Ariz., 45
glacial deposits, Steep Rock Lake, Ont., 539
ground water, Rio Elqui valley, Chile, 491
iron, sedimentation, 357
iron deposits, Minas Gerais, Brazil, 675
iron ores, oxidation, Michigan, 279
isotopic abundances, 176
lead sulfide solubility, 137
liquid inclusions in quartz, 550
metal deposits, geology and geochemistry, 406
metamorphic differentiates, Blackbird district, Idaho, 456
mineral belt, south central Colorado, 209
molybdenum, Rautio, Finland, 713
phosphatized igneous rock deposits, 446
pitchblende deposits, 94
radioactivity of rivers and lakes, Ark., 566
rotation measurements with the ore microscope, 590
serpentines, texture and genesis, 596

Bibliography—*Continued*
synthetic minerals, 304
ulvöspinel and magnetite, 687
uranium, radium, and lead leaching, 368
Billingsley, P. R., and Locke, A., on ore districts, 178
Biltz, W., on lead sulphide, 115
Biogeochemical investigations in Finland (Marmo), 211
Biotite, 452, 454
Blackbird mining district, Lemhi County, Idaho, Metamorphic differentiates in the (Roberts), 447
Blais, R. A., abstract by, 616
Bleeding of chalcocite, 226
Blondel, F., and Marvier, L., review of books by, 422
Bloom, H., abstract by, 322
Blosser, L. G., and Drickamer, H. G., on methane, 22
Boltwood, B. B., on water, 552
Bomi Hill, Liberia, Iron ore at (Fitzhugh), 431
Bond, G., on ironstone, 312
reply to communication by, 501
Bond, G. W., on potash in clay, 699
Books received, 66, 152, 245, 318, 423, 508, 606, 733
Booth, H. S., and Bidwell, R. M., on solutions, 17
Borings, alunite deposits, Pidinga area, South Australia, 692
Rio Elqui valley, Chile, 458
sulphide deposits, Rautio, Finland, 705, 706
Wairakei, New Zealand, 2
Bornite, 78, 622, 625, 631
Boron, 167
Bosazza, V. L., on dyes, 139
Boswell, P. G. H., on clays, 535
Boulders as an aid to ore prospecting in Sweden, Tracing of glacial (Grip), 715
Bowen, N. L., on chromium, 412
on oxides, 402
Bowen, N. L., and Tuttle, O. F., on system MgO—SiO_2—H_2O, 593
Bowley, H., on alunite, 696
Boyle, R. W., abstract by, 617
Bradley, K., review of book by, 243
Bradley, W. F., x-ray identifications by, 101
Bradley, W. H., on thorium dioxide, 147
Bragg, W. L., on ionic radius, 371
Brannock, W. W., *et al.*, on alteration minerals, 11
Brannock, W. W., with Shapiro, L., *A field method for the determination of titanium in rocks*, 282
Brazil, Iron deposits of the Congonhas district, Minas Gerais (Guild), 639
iron ore, canga deposits, 436
Breithauptite, 493, 497
Brewer, A. K., on potassium isotopes, 174
Brewer, A. K., and Baudisch, O., on lithium, 167
Bridgman, P. W., on gases, 16
Brindley, G. W., review of book edited by, 317
British Columbia, lead-zinc, Jersey deposit (abstract), 630
tungsten, Emerald, Feeney, and Dodger deposits (abstract), 615
Broderick, T. M., on martite, 269
Brombert, B. A., reviews by, 64, 65, 152, 315
Brooker, E. J., and Nuffield, E. W., on pitchblende, 362
Brooks, T. B., on iron, 254
Brüggen, J., on Rio Elqui valley, Chile, 458
Bruner, L., and Zawadski, J., on lead sulphide, 115
Bucher, W. H., and Gilkey, A. K., abstract by, 617
Buddington, A. F., on ore deposits, 370
Buerger, N. J., on negative crystals, 548
Building stone, Morton gneiss, Minn., 46
Bunn, C. W., and Emmett H., on sodium chloride, 291
Burbank, W. S., and Goddard, E. N., on Huerfano Park, Colo., 180
on Wet Mtn., Colo., 183
Burbank, W. S., and Henderson, C. W., on Bonanza district, Colo., 180
Burchard, E. F., on iron ore, 670
Buried river valleys and water supplies, Ill., 572
Burwash, E. M., on varves, 537, 539
Bushveld Complex, oxide mineral deposits, 378
Butler, B. S., on ferric oxide, 668
on hematite, 276
Butler, B. S., and Gale, H. S., on alunite, 696
Butler, C. R., on Galena Peak district, Colo., 200

Calcite, 78, 174, 331
decrepitation, 234
decrepitation test, 107
California, geomorphogeny (review), 605
stone (abstract), 330
talc, genesis (abstract), 333
Callaghan, E., on Marysvale district, Utah, 89
Cameron, E. N., abstract by, 323
on rotation properties, 492
Cameron, E. N., and Green, L. H., on ore microscope, 574
rotation properties, 492
Cameron, E. N., Hutchinson, R. W., and Green, L. H., *Sources of error in the measurement of rotation properties with the ore microscope*, 574–590
Cameron, E. N., Rowe, R. B., and Weis, P. L., on inclusions, 541

Campbell, J. A., and Hildebrand, J. H., on xenon, 20
Canada, coal, structure, southern Cordillera (abstract), 625
cobalt, occurrence, 394
geochemical prospecting, eastern Canada (abstract), 629
lithium pegmatites (abstract), 627
pitchblende deposits, 81, 85
Canga, 431, 435, 673
Carbon, isotopic abundances, 167, 600
Carbon dioxide, specific volumes, 33
Carbonates, decrepitation, 233
Carl, H. F., White, H. W., and Hockman, A., abstract by, 323
Carnotite, Colorado, prospecting (review), 314
Cartography (review), 422
Casagrande, A., and Fadum, R. E., on plasticity index of soil, 528
Castaño, J. R., and Garrels, R. M., on iron, 338
Cavinato, A., review of book by, 731
Cerrusite, 203
Cerveira, A., on Urgeirica district, Portugal, 83
Chalazoidite, 3
Chalcocite, 225, 622, 631
Chalcopyrite, 78, 212, 624, 625, 630, 631, 707, 708
Chamberlin, T. C., on iron, 253
Chapinha (iron) ores, Brazil, 672
Charlesworth, J. K., review of book by, 504
Chemical analyses, alunite, Pidinga Lake, South Australia, 693
chromite, Samar, Philippines, 599
dikes, Michigan, 272
gneiss, Minn., 52
granite, Rautio, Finland, 710
ground water, South Australia, 700
hematite ores, Brazil, 660
muck and silt, Steep Rock Lake, Ont., 521
phosphatized felsites, Uruguay, 443
salts in limestones and dolomites, 100
tables, rocks, Wairakei, New Zealand, 8
uranium, 361, 365
water, Rio Elqui, Chile, 474, 485
wolframite, France, 63
Chemical data on the state of supercritical fluids, Review of physico- (Smith), 14
Chert, 259, 264, 444
radiolarian cherts, deposition, Calif., 537
Chhibber, H. L., on steatite, 53
Chhibber, V. N., *Steatite deposits of Bheraghat, Jabalpur district, M. P., India,* 53–57
Chierici, E., on gas, 21
Chile, Geology and ground-water conditions in the lower valley of the Rio Elqui of (Jones), 457
pitchblende, Carrizal Alto district, 83, 89
Chiplonker, G. W., review of book by, 604
Chipman, J., and Murphy, D. W., on iron oxides, 276
Chlorine, isotopic ratios, 173
Chlorite, 89, 261, 452
Chlorite minerals (review), 317
Chloritoid, 451, 454
Christie, A. H., and Kesten, S. U., on Lake Athabasca pitchblende deposit, Saskatchewan, 86
Christie, J. M., and Williams, H. F., on Rio Elqui valley, Chile, 458
Chromite, 378, 404
color dispersion, 578
Philippines, Samar deposits (communication), 598
Chromite deposits of the Bay of Islands igneous complex, western Newfoundland, Origin of the (Smith), 408
Chrysotile, 591
Cinnabar, 136
Clark, A. L., on critical point, 21
Clarke, F. W., on water, 359
on weathering, 273
Clarke, O. M., Jr., *Geochemical prospecting for copper at Ray, Arizona,* 39–45
Clay mineral groups, A qualitative color test for rapid identification of the (Hambleton and Dodd), 139
Clay minerals, 303
structure and x-ray study (review), 317
Clays, genesis (reviews), 243
montmorillonite type, New Zealand, 10
Pidinga alunite area, South Australia, 690
radioactive clays, Colo., 360
varved clays, Steep Rock Lake, Ont., 516, 522
Clegg, K. E., abstract by, 618
Clerical and critical reviews (discussion), 602
Climate, vegetation and man (review), 732
Coal, Alberta (abstract), 618
ash, minor elements (abstract), 332
Canada, structure, Cordillera (abstract), 625
megascopic and microscopic examinations (abstract), 628
metamorphism, Illinois (abstract), 618
Nova Scotia, Sydney and St. Rose fields, petrography (abstract), 619
Sydney field, pyrite occurrences (abstract), 623
origin (review), 244
outbursts in mines (abstract), 620
Cobalt, 79
aplite deposits, Cobalt, Ont. (abstract), 628
geochemistry, 394
Idaho, Blackbird district, 332, 447
Cobalt nickel sulfarsenides and related minerals, Polarization figures and rotation properties as applied to the identification of some (Hutchinson), 492

Cobaltite, 493
Collins, W. H., on cobalt, 394
on micropegmatite, 400
Colloids, iron, precipitation, 654
pitchblende, formation, 92
Collophane, 147
Color test for rapid identification of the clay mineral groups, A qualitative (Hambleton and Dodd), 139
Colorado, Definition of a mineral belt in south central (Gabelman), 177; discussion, 599
pitchblende, Front Range deposits, 82, 88
Uravan mineral belt (review), 314
Colorado Plateau, carnotite, prospecting (review), 314
uraninite deposits (abstract), 625
uranium, deposition controls (abstract), 632
Shinarump conglomerate deposits (abstract), 619
Communications—
Comments on the "porphyry" copper deposits (Schmitt), 416
Improved slide holder for thin sectioning of rocks (Jones), 149
Notes on chromite deposits in Samar, Philippines (Stoll), 598
Puerto Rico bentonite deposit, 239
Congonhas district, Minas Gerais, Brazil, Iron deposits of the (Guild), 639
Cook, K. L., on isotopes, 161
Cooper, L. H. N., on ferric hydroxide, 350
Coordination in ionic crystals, 371
Copper, Arizona, Jerome, geochemical anomaly (abstract), 327
Canada, geochemical prospecting, eastern Canada (abstract), 629
Colorado, Malachite district, 194
Rito Alto district, 204
detection by dithizone, 306, 309
Finland, biogeochemical prospecting, 212
Gaspe Mines, alteration, Que. (abstract), 616
geochemistry, 392, 405
Idaho, Blackbird deposit (abstract), 332
Mexico, Lower Calif. (abstract), 333
nickel-copper ore deposits, 384
Northern Rhodesia, prospecting (review), 243
Northwest Territories, Coppermine River area (abstract), 621
Nova Scotia, Mindamar mine (abstract), 627, 630
Ontario, Falconbridge deposit (abstract), 623
porphyry deposits (communication), 416
Quebec, alteration, northwest Que. (abstract), 626
shale deposits, Germany and Michigan (abstract), 631
Copper—*Continued*
Sweden, prospecting, 717, 721
Utah Copper (review), 313
Copper at Ray, Arizona, Geochemical prospecting for (Clarke), 39
Copper sulfides, Polishing phenomena in the (Wandke), 225
Corby, G. W., *et al.*, review of bulletin by, 418
Corundum, 291, 302
ores, grading (abstract), 323
synthesis (abstract), 325
Cosmology (review), 244
Cotton, C. A., review of book by, 604
Covellite, 225, 708
angle of rotation, 584
Cox, D. C., on Antelope Creek area, Colo., 205
Craig, H., discussion by, 600
Cristobalite, 293, 301
Critical and clerical reviews (discussion), 602
Crockford, M. B. B., abstract by, 618
Cross, C. W., on Westcliff area, Colo., 180
Cuba, chromite, Camaguey district, 411
Cubanite, 708
Curtiss, L. F., and Davis, F. J., on radium, 360
Czechoslovakia, Joachimsthal district, 79

Dahlblom, Th., on chlorides, 98
Daly, R. A., on geothermobaric curves, 31
on rocks, 380
Dams, Chile, sites in Rio Elqui valley, 459
Daunt, J. G., on helium, 166
Davidite, South Australia, Radium Hill mine (abstract), 626
Davis, E. F., on chert, 537
Davis, S. G., review of book by, 64
Davison, E. H., on Cornwall district, England, 84
Debye-Huckel equation, 117
Decrepigraphs, calcite, quartz, and sphalerite, 235
Decrepitation, limestones and dolomites, 105
quartz, Lamaque gold mine, Que. (abstract), 628
O'Brien mine, Que. (abstract), 616
Decrepitation of liquid inclusions (discussion), 233
Decrepitation temperature, 237
Deiss, C. F., abstract by, 324
Delavault, R. E., and Irish, R. I., on copper, 306
Delavault, R. E., with Warren, H. V., and Irish, R. I., *Acetonic dithizone in geochemistry*, 306
Deposition, A study of lead sulfide solubility and its relation to ore (Hemley), 113
Deposits, Geology and geochemistry of base metal (Wilson), 370
de Quervain, F., on building stone, 98

Derby, O. A., on iron, 640
on weathering, 671
Dessau, G., review of report by, 315
Determination of titanium in rocks, A field method for the (Shapiro and Brannock), 282
de Villiers, J. E., on hematite, 670
Dewey, H., on Cornwall district, England, 84
Diagrams—
copper concentration areas, Finland, 218
crystal-liquid equilibrium above critical temperatures, 24
exsolution patterns in magnetite, 679
heating stage, 543
hematite, siderite, and pyrite stability fields, 339
ions, sizes, 375
isotopes of lighter elements, 164
lead sulfide solubility determination apparatus, 120
metal content and mineralogy of pitchblende deposits, 90
quartz pod development during folding, 453
slide holder for thin sections, 149
structure, south central Colorado, 184
system forsterite-anorthite, 413
variation diagrams, alunite, Pidinga, South Australia, 695
vibration directions of reflected light, 576
x-ray spectrometer patterns, antigorite, serpentine and chrysotile, 593
Diamonds, crystallization, 290
Dickinson, S. B., on alunite, 689
Diepen, G. A. M., and Scheffer, F. E. C., on napthalene-ethylene, 28
Differentiates in the Blackbird mining district, Lemhi County, Idaho, Metamorphic (Roberts), 447
Digenite, 225
Dikes, Blackbird district, Idaho, 450, 454
Colorado, south-central Colo., 197, 203
Congonhas district, Brazil, 650, 666, 668
Guadalupe lead-zinc mine, Mexico (abstract), 631
metamorphism of coal, Illinois (abstract), 618
Michigan, iron ranges, 272; (discussion), 726
Mindamar lead-zinc mine, Nova Scotia, 630
sulphide deposits and dikes, 386
Diopside, 56
Discussions—
Banded hematite jaspers of south Singhbhum (Spencer and Percival), 501
Banded hematite quartzites (Spencer and Percival), Dunn, 58
Banded iron formations (Spencer and Percival), Moore, 312; (Moore), Dunn, 729
Discussions—Continued
Corycium defunctum: The non-indicative properties of isotopes and review articles (Jensen), Craig, 600
Definition of a mineral belt in south central Colorado (Gabelman), Peters, 599
Geologic importance of stable isotopic abundances (Jensen) Menke, 728
Origin of the soft iron ores of Michigan (Mann), James, 726
Radioactivity of phosphatic sediments (Ross), McConnell, 147
Sources of error in the decrepitation method of study of liquid inclusions (Stephenson), Smith and Little, 233
Dispersion, arsenopyrite, 498
Dithizone in geochemistry, Acetonic (Warren, Delavault, and Irish), 306
Dix, C. H., review of book by, 151
Dodd, C. G., with Hambleton, W. W., *A qualitative color test for rapid identification of the clay mineral groups,* 139
Dole, M., on oxygen isotopes, 165
Dole, M., and Slobod, R. L., on iron ores, 170
Dolomite, 260, 645
Dolomite sand, 111
Dolomites, Water soluble salts in limestones and (Lamar and Shrode), 97
Dorr, J. V. N., II, on iron formations, 655
Dorr, J. V. N., II, Guild, P. W., and Barbosa, A. L. M., on iron ores, 642
Dorsey, N. E., on water, 15
Drescher-Kaden, F. K., on myrmekite, 712
Dreyer, R., on mercury, 136
Dreyer, R. M., Garrels, R. M., and Howland, A. L., on vacuoles, 548
Du Bois, G. C., on alunite and bauxite, 702
Dunn, J. A., discussions by, 58, 729
on hematite, 502
on quartzites, 61
reply to discussion by, 501

Eastern Hemisphere, petroleum (review), 506
Eastman, D. C., and Evans, R. M., on iron oxide, 277
Eckel, E. B., and Milton, C., *Reconnaissance of superficial phosphate deposit near Minas, Uruguay,* 437–446
Edelman, N., on myrmekite, 710
Edwards, A. B., on martite, 269
on valleriite, 709
Efflorescence from limestone and dolomite, 110
Egli, P. H., on crystals, 291
Eire, geology (review), 504
Eisenstein, A., and Gingrich, N. S., on liquids, 18
Electron micrographs, alunite, Pidinga, South Australia, 698
Elkins, L. E., review of book edited by, 242

Ellsworth, H. V., on radium, 363
Emeléus, H. J., *et al.*, on water, 165
Emmett, P. H., and Schultz, J. F., on iron oxide, 277
Emmons, S. F., on Westcliff area, Colo., 180
Endell, J., Zorn, R., and Hofman, U., on benzidine test, 139
Engineering geology, foundations (review), 244
Engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada (Legget and Bartley), 513
England, iron, Liassic deposits (review), 505
  pitchblende, Cornwall district, 81, 84
Epidote, 712
Epprecht, W., on antigorite, 594
Epstein, S., *et. al.*, on oxygen isotopes, 172
Ercker, L., translation of book by, 505
Eritrea, mineral resources (review), 65
Error in the measurement of rotation properties with the ore microscope, Sources of (Cameron, Hutchinson, and Green), 574
Eskola, P., on metamorphic differentiation, 456
Ethiopia, mineral resources (review), 65
Everhart, D. L., and Wright, R. J., *The geologic character of typical pitchblende veins*, 77–96
  on pitchblende, 91
Experiments, antigorite formation from chrysotile, 595
  clays, identification tests, 140
  Eh and pH measurement, 340
  fluid movements to and from vacuoles, 542
  leaching of ferruginous dolomite, 672
  leaching of limestones and dolomites, 98
  leaching of uranium and radium, 361
  lead sulfide solubility, 119
  sample size reproducibility, 287
Exsolution, cubanite and chalcopyrite, 708
  Fe_2TiO_4 in magnetite, 677

Fairbanks, H. R., and Berkey, C. P., review of book by, 313
Faults, Alberta, coal deposits (abstract), 625
  British Columbia, Salmo district (abstract), 615
  Colorado, south central Colo., 178, 195, 197
  Congonhas district, Brazil, 650, 656, 669
  glacial deposits, Steep Rock Lake, Ont., 518
  Mexico, Guadalupe lead-zinc mine (abstract), 631
  nickel deposit control, 388
  Northwest Territories, Coppermine River region (abstract), 622
Faults—*Continued*
  Ontario, Campbell-Red Lake Mines Ltd., (abstract), 621
    Sudbury district, 399
  Zuni Uplift, New Mexico (abstract), 617
Faust, G. T., on clays, 139
Feldspars, 375, 704
Fenner, C. N., on beidellite, 10
Fenner R., R., on Rio Elqui valley, Chile, 458
Ferberite, 63
Ferguson, J. B., on sulphur, 293
Fermor, L. L., on steatite, 53
Ferrites, 300
Field geology (review), 317
Field method for the determination of titanium in rocks (Shapiro and Brannock), 282
Fieser, L. F., on Fieser solution, 119
  on solutions, 341
Finch, W. I., abstract by, 619
Finland, Biogeochemical investigations in (Marmo), 211
  Molybdenum bearing granite and granodiorite, Rautio (Marmo and Hyvarinen), 704
  ore boulders and prospecting, 715
Fischer, R. P., and Hilpert, L. S., review of paper by, 314
Fischer, R. P., *et al.*, on mineral deposits, 193
Fitzgerald, M. L., on alunite, 689
Fitzhugh, E. F., Jr., *Iron ore at Bomi Hill, Liberia*, 431–446
Flame Fusion Process, 291
Fleischer, M., abstract by, 324
Fletcher, R. A., and Mould, W. P., abstract by, 325
Flint, D. E., de Albear, J. F., and Guild, P. W., on chromite, 411
Flores, R., on Carrizal Alto district, Chile, 89
Fluids, Review of physico-chemical data on the state of supercritical (Smith), 14
Fluorides, 296
Fluorite, 79
  Colorado, south central Colo., 188, 205
  decrepitation test, 107
  Grants area, New Mexico (abstract), 618
  inclusions, 545
Folding, quartz pod development, Idaho, 453
  varve deposits, Steep Rock Lake, Ont., 537
Folds, banded iron formations (discussions), 312, 729
  Blackbird district, Idaho, 450
  Garland and Hot Spring Counties, Ark., 558
  hematite quartzites, India (discussion), 60
  New Mexico, Zuni uplift (abstract), 617

Folds—*Continued*
Ontario, Campbell Red Lake Mines Ltd. (abstract), 621
Fontactoscope, 552
Formulae, activity of ferric to ferrous ion, 349
plasticity index of soil, 528
radon content of water, 553
Foslie, S., on Fe_2TiO_4, 677
Foster, J. W., *Significance of Pleistocene deposits in the ground-water resources of Illinois*, 568–573
Foster, J. W., and Whitney, J. D., on iron, 254
Foster, L. V., on light rays, 575
Foundation engineering (review), 244
Fouque, F., and Michel-Levy, M., on minerals, 289
Fox, W., review of book by, 65
Fractures, New Mexico, Zuni Uplift (abstract), 617
France, tungsten, Puy-les-Vignes and La Chataigneraie deposits (review), 63
Francolite, 147
Frankel, J. J., on calcite, 107
Fraser, H. J., on varves, 535
Frederickson, A. F., on kaolinite, 702
Frenkel, J., on liquids, 18
Frerichs, R., on greenockite, 293
Freyberg, B. v., on iron, 641
Friedman, I. I., on magmatic derivatives, 14
on quartz, 28
Frondel, C., abstract by, 325
Fürth, R., on liquids, 18
Fujii, T., review by, 241

Gabelman, J. W., *Definition of a mineral belt in south central Colorado*, 177–210; discussion, 599
on Pleasant Valley fault, Colo., 184
Galena, 79, 116, 624, 630, 631
Garnets, 450
Garrels, R. M., with Huber, N. K., *Relation of pH and oxidation potential to sedimentary iron mineral formation*, 337
Gases and gaseous solutions, 15, 16
Gatewood, J. S., *et al.*, on phreatophytes, 490
Gathmann, T., on iron ores, 641
Geijer, P., on boulders, 715
Geikie, J., Campbell, R., and Craig, R. M., review of book by, 317
Genesis, Bull-Domingo pipe, Colo. (discussion), 599
clay and laterite (review), 243
iron ores, Congonhas district, Brazil, 640
serpentines, 593
silica in ore deposits (abstract), 628
talc, California (abstract), 333
Geochemical prospecting, Canada, eastern Canada (abstract), 629
Idaho, Blackbird district (abstract), 333
Geochemical prospecting—*Continued*
lead-zinc, Wis.-Ill. district (abstract), 322
United States (abstract), 327
Geochemical prospecting for copper at Ray, Arizona (Clarke), 39
Geochemistry, Acetonic dithizone in (Warren, Delavault, and Irish), 306
gold veins, Yellowknife greenstone belt, Northwest Terr. (abstract), 617
metals, field tests (abstract), 322
niobium and titanium (abstract), 324
uranium and lead, 366
Geochemistry of base metal deposits, Geology and (Wilson), 370
Geologic character of typical pitchblende veins (Everhart and Wright), 77
Geologic history, Colorado, south central Colo., 182
Mexico, Lower Calif. (abstract), 333
Geologic importance of variations in stable isotopic abundances (Jensen), 161
Geologic thermometers, Some considerations regarding liquid inclusions as (Skinner), 541
Geological maps (review), 604
alunite deposits, Pidinga area, South Australia, 691
Bay of Islands igneous complex, Newfoundland, 409
Blackbird district, Idaho, 449
Colorado, south central Colo., 181
Garland and Hot Spring Counties, Ark., 557
Joachimsthal region, Czechoslovakia, 80
Marquette district, Mich., 256
Morton vicinity, Minn., 47
Tennessee (review), 66
Geological Survey of Great Britain (review), 606
Geology, Bay of Islands igneous complex, Newfoundland, 408
Blackbird district, Idaho, 449
Campbell Red Lake Mines, Ltd., Ontario (abstract), 621
coal, Alberta (abstract), 618
Congonhas iron district, Brazil, 643
French Morocco, ore deposits (review), 64
Garland and Hot Spring Counties, Ark., 556
Guadalupe lead-zinc mine, Mexico (abstract), 631
Hong Kong (review), 64
Ireland (review), 504
Labrador Peninsula, iron deposits (abstract), 625
Mexico, ore deposits, Lower Calif. (abstract), 333
Mindamar mine, Nova Scotia (abstract), 627, 630
niobium deposits, U. S. (abstract), 622
Philippines, oil possibilities (review), 418

Geology—*Continued*
Pidinga alunite deposits, South Australia, 689
Radium Hill uranium mine, South Australia (abstract), 626
Ray district, Ariz., 39
Uravan mineral belt (review), 314
Van Horn area, Texas (review), 504
Geology and geochemistry of base metal deposits (Wilson), 370
Geology and ground-water conditions in the lower valley of the Rio Elqui of Chile (Jones), 457
Geomorphology, California, geomorphogeny (review), 605
Geophysical prospecting, Näsliden ore district, Sweden, 720
petroleum, seismic prospecting (review), 151
scintillometer survey, Lac La Ronge district, Sask. (abstract), 624
Geosynclines, itabirite deposition, Brazil, 640, 651, 656
origin, 186
Germanium, occurrence in coal ash (abstract), 332
Germann, A. F. O., and Pickering, S. F., on volatile compounds, 31
Germany, copper, Mansfeld, shale deposits (abstract), 631
pitchblende, Wölsendorf area, 80, 82
Gersdorfite, 628
Gettman, F. H., and Daniels, F., on thermodynamics, 275
Gierer, A., and Wirtz, K., on water, 20
Gilbert, G., on hematite, 668
Giller, E. B., Duffield, R. B., and Drickamer, H. G., on gases, 15
Gingrich, N. S., on liquids, 18
Glacial deposits at Steep Rock Lake, Ontario, Canada, An engineering study of (Legget and Bartley), 513
Glass, 5
Glasstone, S., on vapor, 17
Gneiss, Morton granite (Lund), 46
Gogebic iron range, Mich., 253, 255
Goguel, J., review of book by, 240
Gold, Brazil, itabirite deposits, 648, 668
Colorado, Crestone district, 199
Northwest Territories, Yellowknife greenstone belt (abstract), 617
O'Brien mine, structure and veins, Que. (abstract), 616
Quebec, alteration, northwest Que. (abstract), 626
Goldich, S. S., analysis by, 52
on gneiss, 52
on lateritization, 701
on weathering, 273
Goldschmidt, V. M., on spinel, 677
on the chemical elements, 371
Goranson, R. W., on water, 14
Gossans, lead-zinc deposits (abstract), 622
Goter, E. R., Hudspeth, W. R., and Rainey, D. L., abstract by, 326
Graf, D. F., on dolomite, 112
Grange, L. I., on Wairakei district, New Zealand, 2
Granite, California, stone industry (abstract), 331
Massachusetts, quarrying (abstract), 325
Vermont, Barre district (abstract), 328
Granite and granodiorite, Rautio, Finland, Molybdenum bearing (Marmo and Hyvarninen), 704
Granite gneiss, Morton (Lund), 46
Graphite, 260, 300
carbon isotopic abundances (discussion), 601
United States (abstract), 323
Graphs, angles of rotation correction curve, 586
Eh and pH in ferrous chloride solutions, 342
hydrographs, Rio Elqui valley, Chile, 480
lead sulfide solubility, 123
molybdenum distribution in plants, Finland, 221
silica variation diagrams, 385, 391
soils, physical properties, Steep Rock Lake, Ont., 530
specific volumes of carbon dioxide and water, 32
Graton, L. C., on magmatic derivatives, 14
Gravity ground water, 477
Great Britain, Geological Survey (review), 606
Green, L. H., on angle of rotation, 585
on marcasite, 498
Green, L. H., with Cameron, E. N., and Hutchinson, R. W., *Sources of error in the measurement of rotation properties with the ore microscope*, 574
Greenalite, 260, 726
Greenland, Skaergaard intrusive, copper, 393
Greenockite, 293, 295
Greig, J. W., *et al.*, on magnetite, 269
Greig, J. W., Merwin, H. E., and Posnjak, E., on martite, 269
Grim, R. E., Machin, J. S., and Bradley, W. F., on clays, 140
Grimaldi, F. S., and Fairchild, J. G., on thorium, 360
Grimaldi, F. S., and Levine, H., on uranium, 360
Grip, E., *Tracing of glacial boulders as an aid to ore prospecting in Sweden*, 715–725
Grogan, R. M., and Shrode, R. S., on fluorite, 110
Grosse, E., *et al.*, on iron ores, 641
Ground-water conditions in the lower valley of the Rio Elqui of Chile, Geology and (Jones), 457

Ground-water resources of Illinois, Significance of Pleistocene deposits in the (Foster), 568
Gruner, J. W., on adularia, 12
on feldspars, 712
on iron, 252, 354
on iron and silica, 654
Gruner, J. W., Fetzer, W. G., and Rapaport, I., on Marysvale district, Utah, 89
Grunerite, 263, 267, 726
Guano, 444
Gucker, F. T., and Garrels, R. M., on lead chloride, 126
Guild, P. W., *Iron deposits of the Congonhas district, Minas Gerais, Brazil,* 639–676
Guimarães, D., on itabirite, 641
Guimarães, D., and Barbosa, O., on tuffs, 647
Guntz, A. A., on uranium, 147
Gypsum, 275

Hacquebard, P. A., and Lahiri, K. C., abstract by, 619
Hadlow, L., review of book by, 732
Halite, 329
vacuoles, filling temperatures, 548
Halloysite, 142
Hambleton, W. W., and Dodd, C. G., *A qualitative color test for rapid identification of the clay mineral groups,* 139–146
Hammond, P., on ilmenite, 380
Hannay, J. B., on liquid state, 14
Harand, J., on critical temperature, 21
Harcourt, G. A., on löllingite, 498
Harder, E. C., on iron ores, 641
Harder, E. C., and Chamberlin, R. T., on iron, 640
Harker, A., on carbonate, 276
Harrison, S. F., and Mayer, J. E., on gases, 15
Hase, D. H., on angle of rotation, 584
Hass, W. H., on novaculite, Ark., 558
Hassmann, H., review of book by, 731
Hauser, E. A., on clay minerals, 303
Hauser, E. A., and Legett, M. B., on bentonite, 140
Hawkes, H. E., abstract by, 327
Hawley, J. E., and Robinson, S. C., on iron, 277
Heavy water, 165
Hedvall, J. A., on the solid state, 292
Helium, 166, 728
Hematite, 89, 265, 339, 433, 645, 679
Congonhas district, Brazil, 657
Hindustan, origin of banded jaspers, Singhbhum (discussion), 501
quartzites (discussion), 58
Hemley, J. J., *A study of sulfide solubility and its relation to ore deposition,* 113–138
Hendricks, S. B., and Alexander, L. T., on montmorillonoids, 139
Hess, H. H., Smith, R. J., and Dengo, G., on antigorite, 595
Hevesy, G. von, and Paneth, F., on lead sulfide, 116
Hevesy, G., Hobbie, R., and Holmes, A., on lead, 380
Hildebrand, J. H., and Scott, R. L., on gases, 16
Hill, G. W., review of book by, 244
Hill, W. L., analyses by, 443
Hillebrand, W. F., and Lundell, G. E. F., on uranium, 363
Hills, R. C., on Malachite district, Colo., 194
Hinds, N. E. A., review of bulletin by, 605
History, Geological Survey of Great Britain (review), 606
Utah Copper (review), 313
Hitchen, C. S., on silica, 259
Hjelmquist, S., on ulvöspinel, 678
Högbom, A., on ore boulders, 717
Holland, F. A., Huggill, J. A. W., and Jones, G. O., on helium, 25
Holland, T. H., Hayden, H. H., and Fermor, L. L., on steatite, 53
Holmes, A., on lead, 366
Holmes, R. J., on diarsenides, 492
Holser, W. T., and Schneer, C. J., abstract by, 620
Holtje, R., and Beckert, J., on cupric sulfide, 134
Hong Kong, geology (review), 64
Hosking, J. S., on clay, 699
Hotchkiss, W. O., on iron, 257
Huber, N. K., and Garrels, R. M., *Relation of pH and oxidation potential to sedimentary iron mineral formation,* 337–357
Huff, L. C., abstract by, 327
Hughes, W., on titanium dioxide, 297
Hummel, F. A., on lithium silicates, 303
Hunter, J. F., on Isle area, Colo., 202
Hutchinson, R. W., *Polarization figures and rotation properties as applied to the identification of some cobalt nickel sulfarsenides and related minerals,* 492–500
Hutchinson, R. W., with Cameron, E. N., and Green, L. H., *Sources of error in the measurement of rotation properties with the ore microscope,* 574
Hydrogen, 165
Hydrogen sulfide, 131
Hydrogen sulfide in limestones, 104
Hydrothermal rock alteration at Wairakei, New Zealand (Steiner), 1
Hydrothermal synthesis of minerals, 293
Hyvarninen, L., with Marmo, V., *Molybdenum bearing granite and granodiorite, Rautio, Finland,* 704

Iceland spar, 303
decrepitation test, 107
Idaho, Metamorphic differentiates in the Blackbird mining district, Lemhi County (Roberts), 447
Coeur d'Alene district, structure (abstract), 629
pitchblende, Coeur d'Alene district, 82, 87
Ignatieff, A., abstract by, 620
Igneous rocks, titania content, 285
weathering, 272
Illing, V. C., review of book edited by, 506
Illinois, Significance of Pleistocene deposits in the ground-water resources of (Foster), 568
coal, metamorphism by dikes (abstract), 618
lead-zinc, Wis.-Ill.-Iowa district, prospecting (abstract), 322
Illite, 142
Ilmenite, 379, 380, 405, 622, 678, 686
polarization figures, 583
Inclusions, fluid content, isotopic studies, 169
liquid inclusions, decrepitation (discussion), 233
Morton gneiss, Minn., 48
Inclusions as geologic thermometers, Some considerations regarding liquid (Skinner), 541
Inclusions in limestone, 105
India, Steatite deposits of Bheraghat, Jabalpur district, M.P., (Chhibber), 53
hematite jaspers, origin, Singhbhum (discussion), 501
hematite quartzites (discussion), 58
Indiana, limestone, petrology (abstract), 331
quarry practices (abstract), 329
Ingerson, E., on *Corycium,* 601
on magmatic derivatives, 14
Ingerson, E., and Tuttle, O. F., on willemite, 294
Inoué, S., on polarization figures, 582
Intrusives, gravity settling and isotopic abundances, 172
Ionic size, 371
Ionic strength, activity coefficients, 117
Iowa, lead-zinc, prospecting (abstract), 322
Iozite, 679
Ireland, geology (review), 504
Irish, R. I., with Warren, H. V., and Delavault, R. E., *Acetonic dithizone in geochemistry,* 306
Iron, banded formations (discussion), 312
Colorado, Orient district, 196
England, Liassic deposits (review), 505
hematite jaspers, India (discussion), 501
hematite quartzites (discussion), 58
hydroxides and oxides (review), 317
Labrador Peninsula (abstract), 625
Iron—*Continued*
magnetite, deposition at high temperature (abstract), 620
Michigan, origin (discussion), 726
Ontario, Steep Rock Lake, origin, 670
ore, oxygen isotopic content, 170
ore deposits (review), 422
Union South Africa, Thabazimbi ores, origin, 670
Venezuela, Pao ore, origin, 670
Iron deposits of the Congonhas district, Minas Gerais, Brazil (Guild), 639
Iron formation, titania content, Minn., 285
Iron mineral formation, Relation of pH and oxidation potential to sedimentary (Huber and Garrels), 337
Iron ore at Bomi Hill, Liberia (Fitzhugh), 431
Iron Ore Co. of Canada, Staff, abstract by, 625
Iron ores, Ulvöspinel and its significance in titaniferous (Ramdohr), 677
Iron ores of Michigan, The relation of oxidation to the origin of soft (Mann), 251
Irving, E. M., on oil, 418
Irving, R. D., on iron, 252
Isomorphism, 373
Isotopic abundances, Geologic importance of variations in stable (Jensen), 161
Itabirite, 640, 641, 645
Italy, antimony, Gruppo dei Monti Romani (review), 315
mineral deposits (review), 731
Iwasake, I., and Ishimori, T., on radon, 556

Jabalpur district, M.P., India, Steatite deposits of Bheraghat (Chhibber), 53
Jahns, R. H., abstract by, 328
Jahns, R. H., and Adams, J. W., abstract by, 328
James, H. L., discussion by, 726
on iron, 338
on iron formation, 654
James, W. F., *et al.,* on Great Bear Lake pitchblende deposit, N.W.T., 85
Japan, natural resources (review), 732
phosphate, exploitation of Okinawa deposit, 444
Society of Mining Geologists of Japan, Journal (review), 241
Jarvis, W. L., abstract by, 621
Jenney, C. P., abstract by, 621
Jensen, M. L., *Geologic importance of variations in stable isotopic abundances,* 161–176; discussions, 600, 728
on carbon, 600
Joensuu, O., analyses by, 216, 221
Joints, Zuni Uplift, New Mexico (abstract), 617
Jones, C. L., abstract by, 329
Jones, D. J., communication by, 149

Jones, P. H., *Geology and ground-water conditions in the lower valley of the Rio Elqui of Chile*, 457–491
Jurassic, iron, Liassic deposits, England (review), 505

Kaiser, E. P., abstract by, 622
Kalio-alunite, 696
Kamen, M. D., on isotopes, 161
Kaolin, 142
Kaolin minerals (review), 317
Kaolinite, 5, 274, 689, 693, 695
Kato, H., and Watase, T., on lead sulphide, 115
Kay, M., on a positive island, 192
Keith, M. L., *et al.*, on quartz, 172
Kelley, K. K., on sulfides, 115
Kelley, V. C., on Iceland spar, 107
Kelly, W. C., abstract by, 622
Kennedy, G. C., on inclusions, 541
on liquid state, 14
on silica, 259
Kerr, P. F., review by, 63
Kerr, P. F., and Kulp, J. L., on pitchblende, 85
Kerr, P. F., *et al.*, on clay mineral standards, 140
on Marysvale district, Utah, 89
Kerr, P. F., Hamilton, P. K., and Pill, R. J., on montmorillonoid minerals, 143
Kessler, D. W., and Sligh, W. H., on sulphates, 97
Khitarov, N. I., and Ivanov, L. A., on fluids, 27
Kidd, D. F., and Haycock, M. H., on Great Bear Lake pitchblende deposits, N.W.T., 85
Kielland, J. J., on activity coefficients, 117
Killeffer, D. H., and Linz, A., on molybdenum orange, 296
Kimball, J. P., on iron ores, 254
Kimura, K., *et al.*, on radon, 556
King, D., *Origin of alunite deposits at Pidinga, South Australia*, 689–703
on Pidinga area, South Australia, 689
King, L. H., abstract by, 623
King, P. B., and Flawn, P. T., review of publication by, 504
Klinkenberg, A., on system SiO_2—H_2O, 27
Knight, C. W., on cobalt, 394
Knizek, J. O., and Fetter, H., on alunite, 699
Knox, J., on lead sulphide, 115
Kohl, E., and Haller, H., on Wölsendorf district, Germany, 82
Kohman, T. P., on nuclide, 162
Kolthoff, I. M., on lead sulfide, 115
Kracek, F. C., Morey, G. W., and Merwin, H. E., on system H_2O—B_2O_3, 27
Krauskopf, K. B., on hydrogen sulfide, 131
Krichevsky, I. R., on gas solubility, 16
Krichevsky, I. R., and Tsiklis, D. S., on gases, 16
Krotov, B. P., on dolomites, 98
Kruger, D., and Oberlies, F., on benzidine test, 139
Krumbein, W. C., and Garrels, R. M., on iron, 338
on iron formation, 654
Krustinson, S. J., on siderite, 276
Kubli, H., on dissociation constants, 130
Kuhrt, F., on gases, 16
Kuroda, P. K., Damon, P. E., and Hyde, H. I., on water, 552
Kuroda, P. K., with Arndt, R. H., *Radioactivity of rivers and lakes in parts of Garland and Hot Spring Counties, Arkansas*, 551
Kustinsky, A. F., on lead sulfide, 115

Labrador, geology and ore deposits (abstract), 625
Lake, Ontario, Canada, An engineering study of glacial deposits at Steep Rock (Legget and Bartley), 513
Lakes, lead deposit in Lake Storlaisan, Sweden, 723
Lakes in parts of Garland and Hot Spring Counties, Arkansas, Radioactivity of rivers and (Arndt and Kuroda), 551
Lamar, J. E., and Shrode, R. S., *Water soluble salts in limestones and dolomites*, 97–112
Landslides, Rio Elqui valley, Chile, 463
Steep Rock Lake, Ontario, 520
Lasky, S. G., on hematite, 276
Laterite, 273, 690
Brazil, Congonhas district, 673
genesis (review), 243
Lateritization, alunitization and lateritization, Pidinga, South Australia, 701
Latimer, W. M., on ferric hydroxide, 350
on lead sulfide, 115
Lavas, landscape forms (review), 604
Lazurite, 297
Leaching, iron formation, Mich., 257, 269, 726
itabirite formation, Brazil, 672
limestones and dolomites, 98
Leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions, Notes on the differential (Phair and Levine), 358
Lead, Colorado, Isle and Rito Seco areas, 202, 204
geochemistry, 396, 405
gossans, lead-zinc deposits (abstract), 622
Idaho, Coeur d'Alene district, structure (abstract), 629
Jersey deposit, Brit. Columbia (abstract), 630
Nova Scotia, Mindamar mine (abstracts), 627, 630
Sweden, Laisvall area, prospecting, 723

Lead—*Continued*
Wisconsin-Illinois district, prospecting (abstract), 322
Lead from pitchblende in H_2SO_4 solutions, Notes on the differential leaching of uranium, radium, and (Phair and Levine), 358
Lead sulfide solubility and its relation to ore deposition, A study of (Hemley), 113
Leeston, A. M., translation of book by, 731
Legget, R. F., and Bartley, M. W., *An engineering study of glacial deposits at Steep Rock Lake, Ontario, Canada,* 513–540
Leith, C. K., on weathering, 257
Leith, C. K., and Harder, E. C., on iron, 640
Leith, C. K., and Mead, W. J., on laterite, 273
Leith, C. K., Lund, R. J., and Leith, A., on iron, 257
Lennard phosphors, 298
Lennard-Jones, J. E., on liquids, 18
Lennard-Jones, J. E., and Devonshire, A. F., on liquids, 18
Leonard, R. J., on aluminum sulphate, 701
Lesure, F. G., books received, 66, 152, 245, 318, 423, 508, 606, 733
review by, 731
Letsinger, R. P., abstract by, 329
Levine, H., with Phair, G., *Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions,* 358
Lewis, G. N., and Macdonald, R. I., on heavy water, 165
Liberia, Iron ore at Bomi Hill (Fitzhugh), 431
Lignite, ash, minor-metal content (abstract), 332
Limestone, Indiana, petrology (abstract), 331
quarry practices (abstract), 329
oxygen isotopic abundances, 170
thin-section holder, 149
Limestones and dolomites, Water soluble salts in (Lamar and Shrode), 97
Limonite, 435, 673
Lind, S. C., Underwood, J. E., and Whittemore, C. F., on radium, 364
Lindgren, W., on copper, 194
Liquids, atomic structure, 18
Lithium, 167
alumino lithium silicates, 303
Canada, pegmatite deposits (abstract), 627
North Carolina, Kings Mtn. pegmatites (abstract), 326
Lochhead, D. R., abstract by, 623
Löllingite, 497
Loughlin, G. F., and Koschmann, A. H., on Cripple Creek district, Colo., 207
Lovering, T. S., on Cotopaxi deposit, Colo., 193
on silica, 259
on zeolites, 11
Lovering, T. S., and Goddard, E. N., on Front Range district, Colo., 88
Lucas, G., on limestones, 104
Lund, E. H., *Morton granite gneiss,* 46–52
Lundegårdh, P. H., on zinc, 380

Maass, O., on critical temperature, 21
McConnell, D., discussion by, 147
on apatite, 147
on collophane, 147
MacCormack, K. E., and Schneider, W. G., on carbon dioxide, 15
McIntosh, R. L., and Maass, O., on critical temperature, 21
Mackenzie, G. S., abstract by, 624
McVicker, L. D., analyses by, 100
Maghemite, 682, 686
Magmatic ore deposits, chromite, Bay of Islands complex, Newfoundland, 408
Magmatic oxide mineral deposits, 378
Magnesium, geochemistry, 383
Magness, R. M., analyses by, 443
Magnetite, 89, 261, 277, 300, 404, 433, 657, 658, 677, 685
deposition at high temperature (abstract), 620
titaniferous magnetite, 379
Mahomet buried valley, ground water, Ill., 573
Mallet, F. R., on steatite, 53
Malmqvist, D., on indices of refraction and absorption, 499
Man, climate and vegetation (review), 732
Man and his physical universe (review), 503
Manganese, iron ores, Mich., 272
Mexico, Lower Calif. (abstract), 333
ore boulders, Ultevis Mtn., Sweden, 724
Manitoba, chromite, 378, 382, 411
Flin Flon area, ore deposits, 396, 398
nickel, 386, 389
Mann, V. I., *The relation of oxidation to the origin of soft iron ores of Michigan,* 251–281; discussion, 726
on phosphate, 260
Maps, Brazil, Minas Gerais, Belo Horizonte region, 642
Colorado, south central Colo., 179
cupriferous soils, Ray, Ariz., 42
ground-water areas, Ill., 571
Idaho, Blackbird district, 448
Michigan, Upper Peninsula, 253
Minnesota, Morton vicinity, 47
Nokia and Rautio areas, Finland, 213, 219
Ontario, Rainy Lake region, 514
Philippines, Samar chromite deposits, 598
Pidinga area, South Australia, 690
pitchblende deposits of the world, 84

Maps—*Continued*
Rio Elqui valley, Chile, 460
Sweden, boulder trains, 716
Uruguay, Minas phosphate deposit, 438
Wairakei area, New Zealand, 2
Marble, J. P., on Great Bear Lake pitchblende deposit, N. W. T., 85
Marcasite, 84, 293, 498, 623
Marmo, V., *Biogeochemical investigations in Finland*, 211–224
on sulphides, 709
Marmo, V., and Hyvarinen, L., *Molybdenum bearing granite and granodiorite, Rautio, Finland*, 704–714
Marmo, V., and Mikkola, A., on schists, 212
Marquette iron range, Mich., 255
Mars, K. E., on carbon isotopes, 175
Martite, 267, 657, 658, 665
Mason, B., on *Corycium*, 601
on geochemistry, 371
Massachusetts, granite quarrying (abstract), 325
Mathewson, C. H., review of book edited by, 733
Maucherite, 493, 496
Mawdsley, J. B., abstract by, 624
Mayer, J. E., and Streeter, S. F., on transitions, 22
Mead, W. J., on phosphorus, 273
Measurement of rotation properties with the ore microscope, Sources of error in the (Cameron, Hutchinson, and Green), 574
Meinzer, O. E., on gravity water, 477
Meissner, H., on carbon dioxide, 23
Mellor, J. W., on iron oxides, 276
Menke, J. R., discussion by, 728
Merrill, G. P., on weathering, 273
Mertie, J. B., Jr., abstract by, 330
Merwin, H. E., and Lombard, R. H., on cubanite, 708
Mesquite, copper in leaves, Ariz., 42
Metal deposits, Geology and geochemistry of base (Wilson), 370
Metal ions, geochemistry and distribution, 376
Metallization sequence, 136
Metallogenic epochs, uranium, 77, 83
Metals, field tests (abstract), 322
nonferrous metals, uses (review), 733
rare metals in coal ash (abstract), 332
tests with acetonic dithizone, 306
Metamorphic differentiates in the Blackbird mining district, Lemhi County, Idaho (Roberts), 447
Metamorphic rocks (review), 242
Metamorphism, Blackbird district, Idaho, 451
coal, Illinois (abstract), 618
Colorado, south-central Colo., 201
Congonhas district, Brazil, 648
Metamorphism—*Continued*
myrmekitization, Rautio, Finland, 709, 710
Metasomatic rocks (review), 242
Mexico, lead-zinc, Guadalupe mine (abstract), 631
ore deposits, Lower Calif. (abstract), 333
Mica, 299, 303
atomic structure, 374, 376
hydrous micas, 142
Michels, A., and Michels, C., on carbon dioxide, 34
Michels, A., Bijl, A., and Michels, C., on carbon dioxide, 22
Michels, A., Michels, C., and Wouters, H., on carbon dioxide, 34
Michigan, The relation of oxidation to the origin of soft iron ores of (Mann), 251
copper, Nonesuch shale deposits (abstract), 631
iron, origin (discussion), 726
Mickwitz, A., on lead sulphide, 115
Microscope, Sources of error in the measurement of rotation properties with the ore (Cameron, Hutchinson, and Green), 574
Microscopes, rotation properties study, 588
Microscopy, coal (abstract), 628
Mielenz, R. C., and King, M. E., on dyes, 140
Mielenz, R. C., King, M. E., and Schieltz, N. C., on dyes, 139
Mikkola, T., determinations by, 705
Miller, L. J., abstract by, 625
Milton, C., with Eckel, E. B., *Reconnaissance of superficial phosphate deposit near Minas, Uruguay*, 437
Minas Gerais, Brazil, Iron deposits of the Congonhas district (Guild), 639
Mineral belt in south central Colorado, Definition of a (Gabelman), 177
Mineral deposits, textbook (review), 731
Mineral formation, Relation of pH and oxidation potential to sedimentary iron (Huber and Garrels), 337
Mineral groups, A qualitative color test for rapid identification of the clay (Hambleton and Dodd), 139
Mineral industry, U. S. S. R. (review), 421
Mineral resources, East Africa (review), 65
Hong Kong (review), 65
iron deposits (review), 422
Japan (review), 732
Morocco, French (review), 64
petroleum (reviews), 503, 506
Texas, Van Horn area (review), 504
U. S. S. R. (review), 421
Mineralization, Colorado, south central Colo., 187, 190, 203
copper, porphyry deposits (communication), 416

Mineralization—*Continued*
iron ores, Congonhas district, Brazil, 667
pitchblende, 83, 91
quartz bodies, Blackbird district, Idaho, 455
tungsten, France (review), 63
Salmo, British Columbia (abstract), 615
uranium, sandstones, Colorado Plateau (abstract), 632
Mineralogy, beryl pegmatites, New Mexico (abstract), 328
Colorado, mineral belt, south-central Colo., 190, 195
hematite ores, Congonhas district, Brazil, 657
limestones, Indiana (abstract), 331
lithium minerals in pegmatites, Canada (abstract), 627
ores, tungsten, France (review), 63
oxide minerals of magmatic origin, 376
pitchblende deposits, 77
quartz pods and veins, Blackbird district, Idaho, 453
sulphides, Rautio, Finland, 707
Minerals, Polarization figures and rototation properties as applied to the identification of some cobalt nickel sulfarsenides (Hutchinson), 492
Synthetic (Weyl), 288
analysis and identification (review), 151
oxygen, isotopic abundances, 170
Mines, coal, outbursts (abstracts), 620
Minguzzi, C., on chromium, 148
Mining, pegmatites, North Carolina (abstract), 326
Minnesota, iron formation, titania content, 285
Morton gneiss, 46
Minnesotaite, 263, 267, 726
Models, iron deposit, Bomi Hill, Liberia, 432
Mogensen, E., on Fe_2TiO_4, 677
Molybdenite, 220, 707
polarization figures, 583, 585
Molybdenum, Finland, biogeochemistry, 221
Molybdenum bearing granite and granodiorite, Rautio, Finland (Marmo and Hyvarinen), 704
Molybdenum orange, 295
Monazite, United States, southeast U. S. (abstract), 330
Montana, Coeur d'Alene district, structure (abstract), 629
Montmorillonite minerals (review), 317
Montmorillonoids, 141
Moore, E. S., discussion by, 312
discussion of note by, 729
mention of discussion by, 502
on silica and iron, 312
Morey, G. W., on liquid state, 14
Morey, G. W., and Fenner, C. N., on potassium silicate, 29
Morey, G. W., and Hesselgesser, J. M., on silica, 29
Morey, G. W., and Ingerson, E., on hydrothermal synthesis, 293
on magmatic derivatives, 14
on silica, 259
Morgan, J., and Warren, B. E., on liquids, 18
Morocco, French, ore deposits (review), 64
tin and tungsten, Oulmès deposit (review), 152
Morrell, W. E., and Hildebrand, J. H., on liquids, 18
Morton granite gneiss (Lund), 46
Mott, N. F., and Gurney, R. W., on liquids, 18
Mud runs, Steep Rock Lake, Ont., 520, 523, 526
Müller, H., on Johanngeorgenstadt district, Czechoslovakia, 81
Mullite, 301
Myrmekite, 705

Nagy, B., *Textural pattern of the serpentines,* 591–597
Nagy, B., and Bates, T. F., on serpentines, 591
Native silver, 79
Natural gas, helium isotopic ratios, 166
Texas (review), 316
Neumann H., on zinc, 395
Newberry, J. S., on iron, 254
New Brunswick, metal deposits, northern New Brunswick (abstract), 624
Newfoundland, Origin of the chromite deposits of the Bay of Islands igneous complex, western (Smith), 408
Newhouse, W. H., on inclusions, 114
on sulphides, 386
New Jersey, serpentine, 592
Newland, D. H., on landslides, 520
New Mexico, beryl, Harding pegmatites (abstract), 328
potash, geology (abstract), 329
uranium ore and fractures, Zuni Uplift (abstract), 617
New Zealand, Hydrothermal rock alteration at Wairakei (Steiner), 1
Niccolite, 493, 497
Nickel, 79
Finland, biogeochemistry, 217
geochemistry and ore deposits, 383, 405
Ontario, Falconbridge deposit (abstract), 623
Sweden, Storbodsund area, prospecting, 720, 721
Nickel sulfarenarsenides and related minerals, Polarization figures and rotation properties as applied to the identification of some cobalt (Hutchinson), 492
Nier, A. O., on Great Bear Lake pitchblende deposits, N. W. T., 85

Nier, A. O. C., and Aldrich, L., on helium, 728
Nims, L. F., and Bonner, W. D., on lead sulphide, 115
Niobium, occurrence with titanium (abstract), 324
United States (abstract), 622
Nitrates, sodium nitrate, analysis (review), 505
Nitrogen, isotopic ratios, 168
Nockolds, S. R., and Mitchell, R. L., on chromium, 381
Noddack, I., and Noddack, W., on sulphides, 395
Noguchi, K., on radon, 556
Noll, F. H. W., on liquids, 18
Noll, W., on antigorite, 594
Nonferrous metals, uses (review), 733
Norman, L. A., Jr., abstract by, 330
Norris, D. K., abstract by, 625
North Carolina, monazite (abstract), 330
pegmatites, Kings Mtn. (abstract), 326
Northwest Territories, copper, Coppermine River area (abstract), 621
gold, Yellowknife greenstone belt (abstract), 617
pitchblende, uranium content, 363
pitchblende deposits, 81, 85
sphalerite, decrepitation, 236
Northern Ireland, geology (review), 504
Northern Rhodesia, copper prospecting (review), 243
Norway, sediment deposition in basins, 356
Nova Scotia, coal, Sydney and St. Rose fields, petrography (abstract), 619
Mindamar lead-zinc deposit (abstract), 627, 630
pyrite in coal, Sydney coal field (abstract), 623
Nuclide, 162

Oaks, copper content of leaves, Ariz., 40
Ödman, O. H., and Lundqvist, G., on ore boulders, 717
Ölander, A., and Liander, H., on system NaCl—H_2O, 29
Oertel, A. C., spectrographic determinations by, 696
Ohno, Y., and Matsouka, —., on lime, 112
Ojanperä, P., analyses by, 710
Okinawa, phosphate, Kita Daito deposit, 444
Olivine, 374
O'Neill, T. F., on feldspars, 712
Ontario, Canada, An engineering study of glacial deposits at Steep Rock Lake (Legget and Bartley), 513
Campbell-Red Lake Mines Ltd. (abstract), 621
cobalt-arsenic minerals, Cobalt area (abstract), 628
Falconbridge ore deposit (abstract), 623
iron, Steep Rock Lake, origin, 670
Ontario—Continued
magnetite, Sudbury zone, 379
pitchblende, Montreal River district, 82, 87
Sudbury district, ore deposits, 399
Opal, 5, 89
Ore at Bomi Hill, Liberia, Iron (Fitzhugh), 431
Ore bodies, Campbell Red Lake Mines Ltd., Ontario (abstract), 621
tungsten, Salmo, British Columbia (abstract), 615
Ore deposition, A study of lead sulfide solubility and its relation to (Hemley), 113
Ore deposits (review), 731
Colorado, south central Colo., 177, 187, 189
copper, porphyry deposits (communication), 416
hematite jaspers, origin, Hindustan (discussion), 501
iron (review), 422
Japan (review), 241
Labrador Peninsula (abstract), 625
Mexico, Lower Calif. (abstract), 333
Morocco, French (review), 64
New Brunswick (abstract), 624
niobium, U. S. (abstract), 622
pitchblende veins, 77
Quebec, alteration, northwest Que. (abstract), 626
silica and genesis of ores (abstract), 628
uranium, mineralization of sandstones, Colo. Plateau (abstract), 632
Uravan mineral belt (review), 314
Ore microscope, Sources of error in the measurement of rotation properties with the (Cameron, Hutchinson, and Green), 574
Ore prospecting in Sweden, Tracing of glacial boulders as an aid to (Grip), 715
Ore shoots, Bonanza district, Colo., 195
Ores, Ulvöspinel and its significance in titaniferous iron (Ramdohr), 677
assaying (review), 505
Bonanza district, Colo., 195
corundum, grading (abstract), 323
hematite deposits, Minas Gerais, Brazil, 657
paragenesis, 400
Mindamar lead-zinc mine, Nova Scotia (abstract), 630
uranium, Radium hill mine, South Australia (abstract), 626
Ores of Michigan, The relation of oxidation to the origin of soft iron (Mann), 251
Oriani, R. A., on liquids, 18
Origin, alunite, Pidinga, South Australia, 698
coal and oil (review), 244

Origin—*Continued*
copper "porphyry" deposits (communication), 416
copper-nickel ore, Falconbridge deposit, Ont. (abstract), 623
gold veins, Yellowknife greenstone belt, Northwest Terr. (abstract), 617
hematite jaspers, origin, Hindustan (discussion), 501
hematite ores, Congonhas district, Brazil, 665
hematite quartzites, India, 62
iron ore, Bomi Hill, Liberia, 433, 436
itabirite, Congonhas district, Brazil, 651
myrmekite, Rautio, Finland, 711
phosphate, Minas, Uruguay, 444
rocks, metamorphic and metasomatic (review), 242
steatite, Bheraghat deposit, India, 56
Origin of alunite deposits at Pidinga, South Australia (King), 689
Origin of soft iron ores of Michigan, The relation of oxidation to the (Mann), 251
Origin of the chromite deposits of the Bay of Islands igneous complex, western Newfoundland (Smith), 408
Osborn, E. F., and Tait, D. B., on diopside-forsterite-anorthite, 411
Owen, F. F., and Brinkley, S. R., on ionization constants, 135
Oxidation potential to sedimentary iron mineral formation, Relation of pH and (Huber and Garrels), 337
Oxidation to the origin of soft iron ores of Michigan, The relation of (Mann), 251
Oxide magmatic mineral deposits, 378
Oxides, paragenesis, 402
Oxygen, atomic weights, 163
isotopic ratios, 169

Page, J. B., on benzidine, 139
Paint rock, 274
Palache, C., on ores, Franklin Furnace, N. J., 173
Palache, C., Berman, H., and Frondel, C., on saffiorite, 498
Palache, C., *et al.*, on Stinkkalk, 104
Palygorskite-attapulgite (review), 317
Paragenesis, cobalt-arsenic minerals in aplites, Cobalt, Ont. (abstract), 628
ores, 400
Mindamar lead-zinc mine, Nova Scotia (abstract), 630
pitchblende, 78, 89, 91
tungsten, France (review), 63
Pararammelsbergite, 493, 499
Park, C. F., *et al.*, on itabirite, 645
Parker, C. O., Jr., on Crestone district, Colo., 199
Parkins, L. W., abstract by, 626
Parks, B., on Garland and Hot Spring Counties, Ark., 557
Pattern of the serpentines, The textural (Nagy), 591
Patton, H. B., *et al.*, on lavas, 180
Patton, J. B., abstract by, 331
Pauling, L., on chrysotile, 591
on valency, 372
Pauling's Rule of Valency, 372
Peach, P. A., on calcite, 110
on decrepitation, 233
on temperature scales, 550
Peacock, M. A., and Dadson, A. S., on diarsenides, 492
Peacock, M. A., and Michener, C. E., on diarsenides, 492
Peck, R. B., Hanson, W. E., and Thornburn, T. H., review of book by, 244
Pegmatites, Canada, lithium deposits (abstract), 627
New Mexico, Harding beryl deposits (abstract), 328
North Carolina, Kings Mtn. (abstract), 326
Saskatchewan, Lac La Ronge district (abstract), 624
Penrose, R. A. F., Jr., review of book about, 313
Pentlandite, 384
Percival, F. G., on conglomerates, 58
Perdigones (laterite), Cuba, 673
Periclase, 302
Perovskite, 622
Peters, W. C., discussion by, 599
Petrography, alunite, Pidinga area, South Australia, 693
coal, Sydney and St. Rose fields, Nova Scotia (abstract), 619
granite and granodiorite, Rautio, Finland, 704
Petroleum, Eastern Hemisphere (review), 506
occurrence and recovery (review), 242
origin (review), 244
Philippines, geology (review), 418
seismic prospecting (review), 151
synthetic and refinery products (review), 605
U. S. S. R. (review), 731
Western Hemisphere (review), 503
Pettijohn, F. J., on iron formation, 655
pH and marine carbonate deposition, 654
Phair, G., and Levine, H., *Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 solutions*, 358–369
Phelps, G. W., on clays, 699
Philippines, chromite, Samar deposits (communication), 598
petroleum, possibilities (review), 418
Phosphate deposit near Minas, Uruguay, Reconnaissance of superficial (Eckel and Milton), 437

Phosphatic sediments, radioactivity (discussion), 147
Phosphorous, iron formation, Mich., 272
Phosphors, 298
Photomicrographs, anthophyllite schist, India, 55
chalcocite, 227
dolomite and limestone, 105
felsite and phosphatized rock, 440
hematite after magnetite, Brazil, 658
ilmenite and magnetite, 680
ores, copper, Rautio, Finland, 708
sandstone, Wairakei, New Zealand, 7
serpentine, electron micrograph, N. J., 592
silicates, Michigan, 266
Physico-chemical data on the state of supercritical fluids, Review of (Smith), 14
Physics, textbook (review), 503
Pieruccini, R., on aluminum, 148
Piezoelectric materials, 304
Pigments, synthetic, 295
Pipes, Colorado, Bull-Domingo pipe (discussion), 599
Silver Cliff-Rosita Hills district, 197
Pitchblende, 359, 362
Pitchblende in H_2SO_4 solutions, Notes on the differential leaching of uranium, radium, and lead from (Phair and Levine), 358
Pitchblende veins, The geologic character of typical (Everhart and Wright), 77
Placers, monazite, United States, southeast U. S. (abstracts), 330
Plagioclase, 6
Pleistocene deposits in the groundwater resources of Illinois, Significance of (Foster), 568
Pleonaste, 680, 682, 683
Polarization figures and rotation properties as applied to the identification of some cobalt nickel sulfarsenides and related minerals (Hutchinson), 492
Polishing phenomena in the copper sulfides (Wandke), 225
Polyhalite, 329
Pople, J. A., on liquids, 18
Portugal, pitchblende, Urgeirica deposit, 81, 83
Potash, alunite and rocks, Pidinga area, South Australia, 692
New Mexico, geology (abstract), 329
Potassium, isotopic abundances, 174
Pratt, W. E., reviews by, 418, 506
Pratt, W. E., and Smith, W. D., on Vigo group, 420
Precambrian, Congonhas district, Brazil, 644
Texas, Van Horn area (review), 504
Prehnite, 7
Preston, G. D., on diamond, 290
Price, P., abstract by, 626
Prospecting, biogeochemical methods, Finland, 211, 223
carnotite, Colorado Plateau (review), 314
chromite, Bay of Islands complex, Newfoundland, 410
Colorado, possibilities of south-central Colo., 208
copper, Northern Rhodesia (review), 243
lead-zinc, Wis.-Ill.-Iowa district (abstract), 322
metal deposits, 404
Northwest Territories, Coppermine River region (abstract), 621
pitchblende and uranium deposits, 367
radioactive deposits, 565
Prospecting for copper at Ray, Arizona, Geochemical (Clarke), 39
Prospecting in Sweden, Tracing of glacial boulders as an aid to ore (Grip), 715
Protons, 162
Pseudomorphs, carbonate and magnetite, 61
iron oxides after siderite, 265
Ptilolite, 6, 11
Puerto Rico, bentonite, Aguada deposit (communication), 239
Purdue, A. H., and Miser, H. D., on Blaylock sandstone, Ark., 557
Pyrite, 6, 10, 78, 260, 271, 339, 624, 630, 707, 727
Nova Scotia, Sydney coal field (abstract), 623
prospecting by ore boulders, Sweden, 717, 720
sulphur isotopic content, 173
Pyroxene, atomic structure, 374
Pyrrhotite, 212, 384, 707

Quarries, granite, Massachusetts (abstract), 325
Vermont, Barre district (abstract), 328
limestone, Indiana (abstract), 329
North Carolina, Kings Mtn. pegmatites (abstract), 326
United States (abstract), 324
Quartz, 7, 28, 63, 78, 172, 294, 328, 441, 447, 452, 615, 645, 660, 696
decrepitation, 234
Lamaque gold mine, Que. (abstract), 628
inclusions as thermometers, 541
O'Brien mine, decrepitation, Que. (abstract), 616
Quartzites, hematite quartzites (discussion), 58
Quebec, alteration of wall rock, northwest Que. (abstract), 626
copper, alteration at Gaspe Mines (abstract), 616
geology and ore deposits (abstract), 625
gold, O'Brien mine, structure and veins (abstract), 616

Quebec—*Continued*
ilmenite, Allard Lake deposits, 380
quartz, decrepitation, Lamaque gold mine (abstract), 628
Quinn, E. L., and Jones, C. L., on carbon dioxide, 31

Radioactive minerals, helium isotopic ratios, 166
Radioactivity, influence on origin of oil (review), 242
phosphatic sediments (discussion), 147
Saskatchewan, Lac La Ronge district (abstract), 624
Radioactivity of rivers and lakes in parts of Garland and Hot Spring Counties, Arkansas (Arndt and Kuroda), 551
Radium, and lead from pitchblende in H_2SO_4 solutions, Notes on the differential leaching of uranium (Phair and Levine), 358
absorption by human body, 147
Radon determination of water, 554
Rajagopalan, C., review by, 604
Ralston, O. C., on iron oxides, 276
Ramdohr, P., *Uwöspinel and its significance in titaniferous iron ores*, 677–688
on covellite, 709
on magnetites, 677
on polishing of minerals, 225
Rammelsbergite, 493, 499
Randall, J. T., on liquids, 18
Randall, M., and Spencer, H. M., on lead, 125
Rankama, K., on biogeochemistry, 211
on carbon, 601
on carbon ratios, 167
Rankama, K., and Sahama, T., on *Corycium*, 601
on geochemistry, 371
on potash, 699
on streams, 354
Rare elements, occurrence in coal ash (abstract), 332
Rautio, Finland, Molybdenum bearing granite and granodiorite (Marmo and Hyvarinen), 704
Ravitz, S. F., on lead sulfide, 115
Ray, Arizona, Geochemical prospecting for copper at (Clarke), 39
Razumova, V. N., on dyes, 139
Remberg, H., review of book by, 242
Replacement, felsite by variscite, 441
hematite after magnetite, 658
ores, Mindamar mine, Nova Scotia (abstract), 630
plagioclase by adularia, 6, 12
siderite by magnetite, 262
silicates by sulphides, 389
Reviews—
clerical and critical reviews (discussion), 602

Reviews—Continued
Climate, vegetation and man (Hadlow), 732
Contribution à l'étude des gites de tungstène français. Puy-les Vignes (Haute-Vienne). La Chataigneraie (Weppe), Kerr, 63
Depositi minerari (Cavinato), Lesure, 731
Economics of natural gas in Texas (Stockton, Henshaw, and Graves), 316
Elements of cartography (Robinson), 422
Evolution of the California landscape (Hinds), 605
Foundation engineering (Peck, Hanson, and Thornburn), 244
Fundamental research on occurrence and recovery of petroleum, 1950–51 (Elkins, *et al.*), 242
Geologia e depositi de antimonio e di altri metalli del Gruppe dei Monti Romani (Dessau), Brombert, 315
Geologic map of east Tennessee (Rodgers), 66
Geological maps (Chiplonker), Rajagopalan, 604
Geological Survey of Great Britain (Bailey), 606
Geologie des gites mineraux marocains (Service Géologique du Maroc), Brombert, 64
Geology and mineral deposits of pre-Cambrian rocks of the Van Horn area, Texas (King and Flawn), 504
Geology and oil possibilities of the Philippines (Corby *et al.*), Pratt, 418
Geology of Hong Kong (Davis), 64
Geology of Ireland (Charlesworth), 504
Geology of the Uravan mineral belt (Fischer and Hilpert), 314
Gîtes d'étain et de tungstène de la région d'Oulmès. (Termier, Owodenko, and Agard), Brombert, 152
Identification and qualitative chemical analysis of minerals, 2nd edition (Smith), 151
International Tin Study Group—1952 Statistical Year Book (Fox), 65
Japan's natural resources and their relation to Japan's economic future (Ackerman), 732
Liassic ironstones (Whitehead, *et al.*), 505
Life and letters of R. A. F. Penrose, Jr. (Fairbanks and Berkey), Bateman, 313
Man and his physical universe (Wistar), 503
Minerals—A key to Soviet power (Shimkin), Bateman, 421

Reviews—Continued
Mining Geology: Journal of the Society of Mining Geologists of Japan (Watanabe), Fujii, 241
Modern uses of nonferrous metals (Mathewson *et al.*), 733
Oil in the Soviet Union (Hassmann and Leeston), 731
Origin of metamorphic and metasomatic rocks (Remberg), 242
Problems of clay and laterite genesis. A symposium, 243
Radiant universe (Hill), 244
Record of the rocks (Richards), 243
Risorse minerarie dell'Africa, Orientale, Eritrea—Ethiopia—Somalia (Usoni), Brombert, 65
Science of petroleum, Volume VI, part I. The world's oil-fields. The Eastern Hemisphere (Illing), Pratt, 506
Seismic prospecting for oil (Dix), 151
Structural and field geology (Geikie, Campbell, and Craig), 317
Symmetry (Weyl), Winchell, 151
Symposium sur les gisements de fer du monde (Blondel and Marvier), Bateman, 422
Synthetic products and refinery processes. The science of petroleum, volume V, part II, 605
Traité de tectonique (Goguel), Rodgers, 240
Treatise on ores and assaying (Ercker, Sisco and Smith), 505
Volcanoes as landscape forms (Cotton), 604
Waves and tides (Russell and Macmillan), 316
X-ray identification and crystal structures of clay minerals (Brindley, *et al.*), 317
Reynolds, D. L., on desilicification, 709
Rice, O. K., on liquids, 18
Richards, H. G., review of book by, 243
Richardson, P. W., abstract by, 627
Rittenhouse, G., on clays, 532
Rivers, Amazon River, iron transport, 354, 654, 655
Rio Elqui valley, Chile, 461, 471
Rivers and lakes in parts of Garland and Hot Spring Counties, Arkansas, Radioactivity of (Arndt and Kuroda), 551
Robb, W. L., and Drickamer, H. G., on gases, 15
Roberts, H., and Bartley, M. W., on hematite, 277, 670
on Steep Rock Lake area, Ont., 514
Roberts, J. K., on thermodynamics, 275
Roberts, W. A., *Metamorphic differentiates in the Blackbird mining district, Lemhi County, Idaho*, 447–456
Robin, S., and Vodar, B., on gases, 16
Robin, S., Romand, J., and Oksengorn, B., on gases, 16
Robinson, A. H., review of book by, 422
Robinson, S. C., on Lake Athabasca pitchblende deposit, Saskatchewan, 86
Rock alteration at Wairakei, New Zealand, Hydrothermal (Steiner), 1
Rocks, A field method for the determination of titanium in (Shapiro and Brannock), 282
iron deposits and sediments, 356
metamorphic and metasomatic, origin (review), 242
textbook (review), 243
thin-section holder (communication), 149
Rodgers, J., review by, 240
review of maps by, 66
Roedder, E., on inclusions, 169
Rogers, S. E., and Ubbelohde, A. R., on liquids, 21
Rominger, C., on iron, 255
Rosenqvist, I. T., on ferri-feldspar, 713
Ross, C. S., and Hendricks, S. B., on montmorillonite-like minerals, 10
Ross, V. F., discussion of paper by, 147
Rotation properties as applied to the identification of some cobalt nickel sulfarsenides and related minerals. Polarization figures and (Hutchinson), 492
Rotation properties with the ore microscope, Sources of error in the measurement of (Cameron, Hutchinson, and Green), 574
Rowe, R. B., abstract by, 627
Rubies, synthesis (abstract), 325
Ruhnke, G. H., chemical analyses by, 521
Russell, R. C. H., and Macmillan, D. H., review of book by, 316
Rutile, 296, 622
inclusions in synthetic rubies and sapphires (abstract), 325

Safflorite, 493, 497
Sakamoto, T., on lakes, 356
Sales, R. H., and Meyer, C., on chalcocite, 225
on kaolinite, 274
Salt, New Mexico, potash deposits (abstract), 329
Salt effect, 117, 118
Saltpeter, analysis (review), 505
Salts in limestones and dolomites, Water soluble (Lamar and Shrode), 97
Sampling, clays, Steep Rock Lake, Ont., 528
radium dump material, Colo., 359
reproducibility of sample sizes, 284
Sampson, E., on chromite, 378
Sampson, E., and Hriskevich, M. E., abstract by, 628
Samuel, W., on Steep Rock Lake, Ont., 514

Sandell, E. B., on photometric procedure, 122
Sandell, E. B., and Goldich, S. S., on copper, 380
Sanders, B. H., on hematite, 641
Sandstones, Colorado Plateau, uranium deposition controls (abstract), 632
Uravan mineral belt (review), 314
Sapphire, synthesis (abstract), 325
Saskatchewan, Flin Flon area, ore deposits, 396, 398
pitchblende, Goldfields district, 81, 86
Sauramo, M., on boulder trains, 715
Schaffer, R. J., on sulphates, 97
Scheelite, 291, 615
Schmidt, R. G., determinations by, 285
Schmitt, H., abstract by, 628
communication by, 416
on alumina, 416
on solutions, 11
Schneider, W. G., on liquids, 18
Schröer, E., on critical point, 21
Schulman, J. H., Claffy, E. W., and Ginther, R. J., on quartz, 293
Schwartz, G., on alumina, 416
Schwartz, G. M., on cubanite, 708
Schwellnus, C. M., and Willemse, J., on magnetite, 381
Scientific Notes and News, 74, 159, 247, 335, 428, 511, 633, 739
Scorodite, 718
Scott, H. S., on decrepitation, 233
Sections, alteration zones, Wairakei, New Zealand, 4
alunite deposits, Pidinga area, South Australia, 691
Bay of Islands intrusive, Newfoundland, 412
borings at Rautio, Finland, 706
Bushveld Complex, oxide layers, composition, 381
copper deposits, Ray, Ariz., 43
iron deposit, Bomi Hill, Liberia, 433
Rio Elqui valley, Chile, 471
Rockford, Ill., 572
Sederholm, J. J., on myrmekite, 711
Sedimentary iron mineral formation, Relation of pH and oxidation potential to (Huber and Garrels), 337
Sedimentation, iron deposits, 355
Sediments, coal, Alberta (abstract), 618
Congonhas district, Brazil, 644
Fraser River estuary, Brit. Columbia, 524
hematite jaspers, origin, Hindustan (discussion), 501
ironstones, Liassic, England (review), 505
limestone, Indiana, Salem limestone (abstract), 331
phosphates, radioactivity (discussion), 147
Sediments—*Continued*
sandstones, uranium deposition controls, Colorado Plateau (abstract), 632
shales, copper deposits, Germany and Michigan (abstract), 631
Steep Rock Lake, Ont., 513
uranium deposits in Shinarump conglomerate, Colo. Plateau (abstract), 619
Seismic prospecting for oil (review), 151
Seismology, seismic prospecting for oil (review), 152
Seitsaari, J., on myrmekitization, 710
Selfridge, G. C., on serpentine minerals, 591
Sepiolite (review), 317
Sericite, 6
Serpentines, The textural pattern of the (Nagy), 591
Philippines, Samar, 598
Shales, black shales, radon content, Ark., 551, 556
copper deposits, Germany and Michigan (abstract), 631
Shand, S. J., on thiophile elements, 373
Shapiro, L., and Brannock, W. W., *A field method for the determination of titanium in rocks*, 282–287
Shimkin, D. B., review of book by, 421
Shrode, R. S., with Lamar, J. E., *Water soluble salts in limestones and dolomites*, 97
Siderite, 5, 10, 63, 78, 254, 260, 266, 339
Siegl, W., on benzidine test, 139
Silica, 259, 652
genesis and ore deposits (abstract), 628
migration, Blackbird district, Idaho, 454, 456
origin, India (discussion), 502
solubility, 30
Silicates, atomic structures, 373
Silication, 202, 726
Sills, Saskatchewan, Lac La Ronge district (abstract), 624
Silver, 631
Colorado, Bonanza district, 195
Idaho, Coeur d'Alene district, structure (abstract), 629
Sweden, Harmsarvet area, prospecting, 722
Sisco, A. G., and Smith, C. S., review of translation by, 505
Skinner, B. J., *Some considerations regarding liquid inclusions as geologic thermometers*, 541–550
Slags, sulphur solubility of slags, 391
Slate, titania content, Minn., 285
Slickensides, quartz pods, Blackbird district, Idaho, 452
Smith, C. H., *Origin of the chromite deposits of the Bay of Islands igneous complex, western Newfoundland*, 408–415

Smith, F. G., *Review of physico-chemical data on the state of supercritical fluids*, 14–38
abstract by, 628
on decrepitation, 233
on sulfides, 115
Smith, F. G., and Little, W. M., discussion by, 233
Smith, F. G., and Peach, P. A., on decrepitation, 233
Smith, F. G., *et al.*, on inclusions, 549
Smith, O. C., review of book by, 151
Smith, W. D., on sediments, 420
Smoke, copper transport, 41
Snelgrove, A. K., Seaman, W. A., and Ayres, V. L., on greenalite, 260
Sobolev, N. D., on chrysotile, 596
Society of Economic Geologists, 71, 321, 322, 613
Program and abstracts of papers to be presented at the Toronto Meeting, Nov. 9–11, 1953, 613
Sodium chloride, crystallization, 290
Sodium nitrate, 303
Soil mechanics (review), 244
Soils, copper content, Ray, Ariz., 42
varved soils, Steep Rock Lake, Ont., 527
Solid state reactions, 292
Solubility and its relation to ore deposition, A study of lead sulfide (Hemley), 113
Solubility product, 116
Solutions, Notes on the differential leaching of uranium, radium, and lead from pitchblende in H_2SO_4 (Phair and Levine), 358
Somaliland, mineral resources (review), 65
Somers, G., abstract by, 628
Sorby, H. C., on inclusions, 542
Sosman, R. B., and Hostetter, J. C., on martite, 267
South Australia, Origin of alunite deposits at Pidinga (King), 689
South Carolina, monazite (abstract), 330
Spangler, R. D., on liquids, 18
Spectrometer, mass spectrometer, 163, 175
Specularite, 667
Spencer, E., and Percival, F. G., discussion by, 501
discussions of articles by, 58, 312
Sphalerite, 79, 212, 624, 630, 631
decrepitation, 234
Spicer, H. C., on geothermal gradients, 31
Spinel, 301, 377, 410
Splines, 226
Spodumene, 326
Canada, pegmatite deposits (abstract), 627
helium content, isotopic ratios, 166
Springs, Bull-Domingo pipe, Colo. (discussion), 599
hot springs, Poncha Springs, Colo., 206
Springs—*Continued*
New Zealand, Wairakei thermal springs, 1
Rio Elqui valley, Chile, 481, 486
Stadnichenko, T., abstract by, 332
Steatite deposits of Bheraghat, Jabalpur district, M.P., India (Chhibber), 53
Steep Rock Lake, Ontario, Canada, An engineering study of glacial deposits at (Legget and Bartley), 513
Steiner, A., *Hydrothermal rock alteration at Wairakei, New Zealand*, 1–13
Step, J., and Becke, F., on Joachimsthal district, Czechoslovakia, 79
Stephens, F. J., on Cornwall district, England, 84
Stephenson, T. E., discussion of paper by, 233
Stevens, R. E., on chromite, 379
Stewart, G. W., on liquids, 18
Stibnite, 226
Stilpnomelane, 263, 267, 726
Stockton, J. R., Henshaw, R. C., Jr., and Graves, R. W., review of book by, 316
Stockwell, C. H., on chromite, 378
Stoll, W. C., communication by 598
Stone, J. B., on Orient district, Colo., 196
Stone, California (abstract), 330
United States, review (abstract), 324
Stratigraphy, Bay of Islands complex, Newfoundland, 409
Colorado, south central Colo., 182
Congonhas district, Brazil, 644
Garland and Hot Spring Counties, Ark., 556
Philippines (review), 419
Pidinga area, South Australia, 692
Rio Elqui valley, Chile, 465
Rockford area, Ill., 572
Texas, Van Horn area (review), 504
Wairakei district, New Zealand, 3
Straub, F. G., on salts, 27
Strengite, 437, 439
Strese, H., and Hofman, U., on antigorite, 594
Strøm, K. M., on basins, 356
Structural geology (review), 317
Structure, coal deposits, Canadian Cordillera (abstract), 625
Coeur d'Alene district, Idaho-Montana (abstract), 629
Colorado, south central Colo., 183, 192
Congonhas district, Brazil, 648, 661
Garland and Hot Spring Counties, Ark., 558
iron deposit, Bomi Hill, Liberia, 432, 433
New Mexico, Zuni Uplift (abstract), 617
O'Brien mine area, Que. (abstract), 616
Philippines (review), 419
pitchblende veins, 78, 89, 92
Rio Elqui valley, Chile, 468
textbook (review), 240
Stupalith, 303

Sturges, W. B., and Cameron, E. N., on lead, 135
Sulfarsenides and related minerals, Polarization figures and rotation properties as applied to the identification of some cobalt nickel (Hutchinson), 492
Sulfide solubility and its relation to ore deposition, A study of lead (Hemley), 113
Sulfides, Polishing phenomena in the copper (Wandke), 225
copper and molybdenum, Rautio, Finland, 704
Finland, sulphide schists, 212
Sweden, ore boulder prospecting, 717
Sulphur, geochemistry, 384, 390
isotopic ratios, 173
Sulphur control of lead solubility, 131
Sundberg, K., Lundberg, H., and Eklund, J., on ore boulders, 717
Supercritical fluids, Review of physicochemical data on the state of (Smith), 14
Sweden, Tracing of glacial boulders as an aid to ore prospecting in (Grip), 715
Syenite, radioactivity, Ark., 560, 564
Sylvite, synthesis, 291
Symmetry (review), 151
Synthesis, adularia, 12
antigorite and chrysotile, 593
rubies and sapphires (abstract), 325
Synthetic minerals (Weyl), 288

Tables, chemical analyses, alunite, Pidinga Lake, South Australia, 693
dikes, Michigan, 272
gneiss, Minn., 52
granite, Rautio, Finland, 710
hematite ores, Brazil, 660
leaves, Ray, Ariz., 40
muck and silt, Steep Rock Lake, Ont., 521
rocks, Wairakei, New Zealand, 8
salts in limestones and dolomites, 100
uranium, 361, 365
water, Rio Elqui, Chile, 474, 485
chemical elements in rock types, 380
cobalt-nickel sulfarsenides, rotation properties, 493
decrepitation temperatures, 237
ilmenite and molybdenite, polarization figures, 583, 585
isotopic abundances, 166
itabirite, physical properties, 652
leach solids from limestones and dolomites, 99
metals, field tests (abstract), 322
mineral deposits, south central Colorado, 188
montmorillonoid minerals, tests, 143
pitchblende deposits, geology, 78, 89
plagioclase, Rautio, Finland, 705
radon content of waters, 553
Tables—*Continued*
solubility of lead sulfide, 115
stratigraphy, Bay of Islands intrusive, Newfoundland, 412
Congonhas district, Brazil, 644
Pidinga area, South Australia, 692
Rockford area, Ill., 572
Wairakei area, New Zealand, 3
system H_2O—Na_2O—SiO_2, fluid immiscibility, 28
titanium content of rocks, 285
vacuoles, filling temperatures, 546, 548
water, flow and analyses, Rio Elqui, Chile, 472, 485
Taggart, A. F., on galena, 116
Talc, 274, 647, 650, 660, 667, 726
California, genesis (abstract), 333
India, Bheraghat deposits, 53
Tapp, J. S., Steacie, E. W. R., and Maass, O., on critical temperature, 21
Teays buried valley, ground water, Ill., 573
Technique, aluminum phosphate manufacture, Japan, 445
analysis of leaves for copper, 39
apparatus for measurement of Eh and pH, 340
clay mineral identification, 140
copper determination of ground water, 214
decrepitation of liquid inclusions, 233
determination of hydraulic characteristics of aquifers, Chile, 487
geochemical prospecting tests (abstract), 322
holder for thin sections, 149
leaching of limestones and dolomites, 98
polarization figures and rotation properties, sulfarsenides, 494
polishing copper sulfides, 231
quarrying limestone, Indiana (abstract), 329
radon measurements of water, 552
solubility determination of lead sulfide, 119
synthesis of minerals, 289
titanium determination in rocks, 282
ulvöspinel identification, 686
vacuoles, heating and examination, 542
Tennantite, 630
Tennessee, geologic map, east Tenn. (review), 66
Termier, H., Owodenko, B., and Agard, J., review of book by, 152
Terraces, Rio Elqui valley, Chile, 471
Terzaghi, K., on landslides, 520
Test for rapid identification of the clay mineral groups, A qualitative color (Hambleton and Dodd), 139
Tetrahedrite, 87
color dispersion, 578
Texas, natural gas (review), 316
Van Horn area (review), 504

Textbooks, man and his physical universe (review), 503
mineral deposits (review), 731
rocks (review), 243
structural geology (review), 240
Textural pattern of the serpentines (Nagy), 591
Thayer, T. P., on chromite, 383, 411
Theis, C. V., on coefficient of transmissibility, 487
Thermometers, Some considerations regarding liquid inclusions as geologic (Skinner), 541
Thiel, G. A., and Dutton, C. E., on stone, 46
Thode, H. G., on isotopes, 161
Thode, H. G., *et al.*, on boron, 167
Thode, H. G., Macnamara, J., and Collins, C. B., on sulphur isotopes, 173
Thoreau, J., and Trieu de Terdonck, R., on Shinkolobwe mine, Belgian Congo, 78
Thurlow, E. E., and Wright, R. J., on Coeur d'Alene district, Idaho, 87
Tides (review), 316
Tin, French Morocco, Oulmès region (review), 152
Statistical Yearbook (review), 65
Titaniferous iron ores, Ulvöspinel and its significance in (Ramdohr), 677
Titanium, 405
occurrence with niobium (abstract), 324
Titanium in rocks, A field method for the determination of (Shapiro and Brannock), 282
Titanium oxide, loss during oxidation, Mich., 272
Titanomorphite, 6
Transvaal, Bushveld Complex, oxide mineral deposits, 378
Treadwell, W. D., and Hepenstrict, H., on silver sulfide, 128
Tremolite, 333
Tritium, 166
Trofimov, A. V., on carbon, 601
Troilite, 391
Trumpler, G., on lead sulfide, 116
Tu, K. C., on serpentine, 594
Tucholski, T., on water, 165
Tungsten, British Columbia, Emerald, Feeney, and Dodger deposits (abstract), 615
France, Puy-les-Vignes and La Chataigneraie deposits (review), 63
French Morocco, Oulmès deposit (review), 152
Tunnels, Belo Horizonte area, Brazil, 670, 671
Turkevich, J., and Hillier, J., on chrysotile, 591
Turner, A. F., Benford, J. R., and McLean, W. J., on light, 583
on stibnite, 226
Turner, F. J., on metamorphic differentiation, 456
Tuttle, O. F., and Friedman, I. I., on magmatic derivatives, 14
Twenhofel, W. S., on inclusions, 545
Tyler, S. A., on iron, 252
on itabirite, 641

Ullmanite, 493, 496
Ultramarine, 297
Ulvöspinel and its significance in titaniferous iron ores (Ramdohr), 677
Umangite, angle of rotation, 584
Underground water, analyses, western South Australia, 700
Finland, geochemistry, 212
Rio Elqui valley, Chile, 476, 485
Union South Africa, iron, Thabazimbi ores, origin, 670
U.S.S.R., mineral resources (review), 421
petroleum (review), 731
United States, coal, minor elements in ash (abstract), 332
geochemical prospecting (abstract), 327
graphite (abstract), 323
monazite, southeast U. S. (abstract), 330
niobium (abstract), 622
stone in 1952 (abstract), 324
Universe (review), 244
Universe and man (review), 503
Uraninite, Colorado Plateau deposits (abstract), 625
Saskatchewan, Lac La Ronge pegmatite (abstract), 624
Uranium, 148
radium, and lead from pitchblende in H_2SO_4 solutions, Notes on the differential leaching of (Phair and Levine, 358
Colorado Plateau, deposition controls in sandstone (abstract), 632
origin, 173
New Mexico, Zuni Uplift (abstract), 617
Radium Hill mine, South Australia (abstract), 626
Shinarump conglomerate deposits, Colo. Plateau (abstract), 619
Uravan mineral belt (review), 314
Urey, H. C., on isotopes, 161
Urey, H. C., *et al.*, on oxygen isotopes, 171
Uruguay, Reconnaissance of superficial phosphate deposit near Minas (Eckel and Milton), 437
Usoni, L., review of book by, 65
Utah, pitchblende, Marysvale district, 83, 89
uranium, Shinarump conglomerate deposits (abstract), 619
Utah Copper, history (review), 313

Vacuoles, 541
Väyrynen, H., on granodiorite, 710
Valleriite, 709

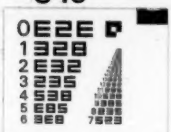
Vanadium, 404
van der Walt, C. F. J., on chromite, 378
Vanderwilt, J. W., Burbank, W. S., and Traver, W. M., Jr., on Malachite district, Colo., 194
Van Diest, E. C., and Van Diest, P. H., on limestone, 204
Van Hise, C. R., on iron, 253
Van Hise, C. R., and Bayley, W. S., *et al.*, on carbonates, 255
Van Hise, C. R., and Leith, C. K., on iron, 252
Variscite, 437, 439, 442
Varves, light and dark varves, physical properties, 529
Vegetation, man, and climate (review), 732
Veins, The geologic character of typical pitchblende (Everhart and Wright), 77
Blackbird district, Idaho, 447
Bonanza district, Colo., 195
Campbell Red Lake Mines Ltd., Ontario (abstract), 621
gold, Quebec, decrepitation of quartz (abstract), 628
O'Brien mine (abstract), 616
Yellowknife greenstone belt, Northwest Terr. (abstract), 617
pitchblende and uranium veins, 91
tungsten, Leucamp, France (review), 63
Venezuela, iron, Cerro Bolivar and Pao ores, 435, 670
Verhoogen, J., on lead sulfide, 115
Vermiculite (review), 317
Vermont, granites, Barre district (abstract), 328
Verneuil, A., on rubies, 289
Verneuil Process, 291
Vhay, J. S., abstract by, 332
on Blackbird district, Idaho, 447
Viebig, W., on Johanngeorgenstadt district, Czechoslovakia, 81
Vineyard, G. H., on argon, 16
Vogt, J. H. L., on itabirite, 641
on titanium, 379
Volcanoes, landscape forms (review), 604
Vugs, occurrence, Japan, Ashio mine (review), 241

Wadsworth, M. E., on iron, 255
Wager, L. R., and Deer, W. A., on Skaergaard intrusive, Greenland, 172
Wager, L. R., and Mitchell, R. L., on chromium, 381
Wagman, D., *et al.*, on fluid reactants, 276
Wairakei, New Zealand, Hydrothermal rock alteration at (Steiner), 1
Wallace, R. E., and Hobbs, S. W., abstract by, 629
Wandke, A. D., *Polishing phenomena in the copper sulfides*, 225–232
Wang, J. H., on liquids, 18
Ward, L. K., on opal, 692
Warnes, A. R., on limestones, 98
Warren, B. E., on glass, 19
Warren, B. E., and Hering, K. W., on chrysotile, 591
Warren, H., and Delavault, R. V., abstract by, 629
Warren, H. V., Delavault, R. E., and Irish, R. I., *Acetonic dithizone in geochemistry*, 306–311
Warren, H. W., and Howatson, G. H., on plants, 212
Wartenberg, H. von, on oxides, 294
Wasastjerna, J. A., on ions, 371
Washington, H. S., on the chemical elements, 370
Watanabe, T., review of books edited by, 241
Water, atomic structure, 20
oxygen isotopic abundances, 170
specific volumes, 32
Watson, K. D., abstract by, 630
Waves (review), 316
Weathering, basic igneous rocks, 273
hematite ores, Congonhas district, Brazil, 674
iron ore, Bomi Hill, Liberia, 435
itabirite, Brazil, 671
lead-zinc gossans (abstract), 622
nickel silicate deposits, 389
pyrite in coal, Nova Scotia, Sydney field (abstract), 623
Webb, J. S., and Millman, A. P., on plants, 212
Weeks, L. G., on geosynclines, 186
Weigel, O., on lead sulphide, 115
Weil-Malherbe, H., and Weiss, J., on clays, 140
Weir, D. B., review of paper by, 314
Wells, A. F., on ions, 372
Wells, water wells, Rio Elqui valley, Chile, 485, 486
Wenzel, L. K., on transmissibility, 489
Weppe, M., review of bulletin by, 63
West, C. D., on mica, 303
Western Hemisphere, petroleum (review), 503
Weyl, H., review of book by, 151
Weyl, W. A., *Synthetic minerals*, 288–305
Whishaw, Q. G., abstract by, 630
White, W. C., and Yagoda, H., on nitrogen, 168
White, W. S., abstract by, 631
Whitehead, G., and Dorr, J. V. N., II, on Itabira district, Brazil, 643
Whitehead, T. H., *et al.*, review of memoir by, 505
Whitehouse, F. W., on lateritic profile, 690
Whiting, F. B., abstract by, 631
Whitney, J. D., on iron, 254
Wickman, F. E., on graphs, 365
Wickman, F. E., and von Ubisch, H., on graphite, 601
Wickman, F. E., Blix, R., and von Ubisch, H., on carbon ratios, 168

Wild, R. L., on nitrogen, 16
Wilde, W. T., and Rees, W. J., on chromium, 412
Willard, M. E., and Proctor, P. D., on alunite, 699
Willemite, 294
Willis, B., on sediments, 420
Wilson, H. D. B., *Geology and geochemistry of base metal deposits*, 370–407
Wilson, —., on water, 11
Winchell, A. N., on aphrosiderite, 261
Winchell, H., review by, 151
Wisconsin, lead-zinc, Ill.-Wis.-Iowa district, prospecting (abstract), 322
Wisser, E., abstract by, 333
on basement complex, Philippines, 420
Wistar, R., review of book by, 503
Wolframite, 63
World, petroleum, Eastern Hemisphere (review), 506
Western Hemisphere (review), 503
Wright, C. E., on iron, 253
Wright, F. E., on polarization figures, 582
Wright, H. D., on Montreal River district, Ontario, 87
Wright, L. A., abstract by, 333
Wright, R. J., abstract by, 632
on uranium veins, 91
Wright, R. J., with Everhart, D. L., *The geologic character of typical pitchblende veins*, 77
Wyoming, chromite, Caspar Mtn., 383

X-ray diffraction patterns, alunite, South Australia, 692, 697
X-ray studies, clay minerals (review), 317
gases, 16
X-ray studies—*Continued*
glasses and liquids, 19
leach solids from dolomites and limestones, 101
pitchblende, 362
Xylene emulsion, 307

Yamanari, F., on phosphate, 444
Yamomoto, T., on chlorides, 290
Yoder, H. S., on serpentine, 594
Yoe, J. H., and Armstrong, A. R., on titanium, 282

Zeolitization, 6, 11
Zerfoss, S., Johnson, L. R., and Imber, O., on piezoelectric materials, 304
Zinc, Arizona, Jerome, geochemical anomaly (abstract), 327
Canada, geochemical prospecting, eastern Canada (abstract), 629
detection by dithizone, 309
Finland, biogeochemistry, 213
geochemistry, 395, 405
gossans, lead-zinc deposits (abstract), 622
Jersey deposit, Brit. Columbia (abstract), 630
Näsliden area, prospecting, Sweden, 720
Nova Scotia, Mindamar mine (abstracts), 627, 630
Wisconsin-Illinois district, prospecting (abstract), 322
Zlavyansky, V. T., on liquids, 19
ZoBell, C. E., on redox solution, 341
Zones of alteration, Wairakei, New Zealand, 1
Zoning, ore bodies, 400

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